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Distinctions between orthographic long-term memory and working memory

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Abstract

Research in the cognitive and neural sciences has long posited a distinction between the long-term memory (LTM) storage of information and the short-term buffering of information that is being actively manipulated in working memory (WM). This basic type of distinction has been posited in a variety of domains, including written language production—spelling. In the domain of spelling, the primary source of empirical evidence regarding this distinction has been cognitive neuropsychological studies reporting deficits selectively affecting what the cognitive neuropsychological literature has referred to as the orthographic lexicon (LTM) or the graphemic buffer (WM). Recent papers have reexamined several of the hallmark characteristics of impairment affecting the graphemic buffer, with implications for our understanding of the nature of the orthographic LTM and WM systems. In this paper, we present a detailed case series study of 4 individuals with acquired spelling deficits and report evidence from both error types and factors influencing error rates that support the traditional distinction between these cognitive systems involved in spelling. In addition, we report evidence indicating possible interaction between these systems, which is consistent with a variety of recent findings in research on spelling.

Keywords

Orthography; Spelling; Long-term memory; Working memory

Researchers in cognitive psychology and neuroscience have long proposed that the cognitive and neural systems involved in the long-term retention of information are distinct from those involved in the temporary storage of information being actively manipulated during processing—a distinction between what is typically referred to as long-term memory (LTM) and working memory (WM; Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974). This distinction has been examined in considerable detail in a wide variety of cognitive domains and tasks (e.g., list memory, sentence comprehension, mental arithmetic, and syllogistic reasoning, among others) and has been supported by behavioural observations of neurologically intact as well as neurologically impaired populations. Nonetheless, the specific characteristics of these memory systems and their relationship remain disputed with

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proposals varying in both the characteristics of the WM system and the degree to which the two systems are independent (see Miyake & Shah, 1999, and papers therein). In this paper, we evaluate the long-term versus working memory distinction within the domain of written language production—spelling—specifically considering evidence from several cases of acquired dysgraphia.

Considerable research indicates that spelling relies on both LTM and WM systems. Specifically, spelling is proposed to include (among others) a process responsible for the retrieval/activation of a word's spelling in long-term memory (this long-term memory repository is typically referred to as the orthographic output lexicon), as well as a working memory system (typically referred to as the graphemic buffer) that ensures that each of the word's component letters is selected for production in the appropriate order. The working memory process interfaces with the motor systems involved in either written (production of letter shapes) or oral spelling (production of letter names). Cognitive neuropsychological findings of double dissociations between long-term memory and working memory deficits in spelling have formed the bulk of the evidence supporting the long-term versus working memory distinction in spelling (Badecker, Hillis, & Caramazza, 1990; Caramazza, 1988; Caramazza & Miceli, 1990; Caramazza, Miceli, & Villa, 1986; Caramazza, Miceli, Villa, & Romani, 1987; Ellis, 1984; Kay & Hanley, 1994; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994; Miceli, Silveri, & Caramazza, 1985; see Rapp, 2002, for a review). However, while not directly challenging this distinction, recent work by Sage and Ellis (2004) has questioned several lines of evidence that have been used to support the distinction. In this paper, we consider the specific arguments put forward by Sage and Ellis (2004) and, more generally, examine the relationship between these purportedly independent memory systems. In the introduction, we summarize existing claims regarding LTM and WM components of the spelling system, and we consider recent data that may be problematic for the two-systems account in spelling. In the body of the paper, we present data from four dysgraphic individuals that support the traditional distinction between LTM and WM systems in spelling, while at the same providing some evidence regarding the interactive relationship between them.

Long-term memory and working memory in spelling

Figure 1 depicts a traditional information-processing account of the cognitive processes active in spelling a word (e.g., *yacht*) in response to auditory presentation of the word (e.g., [yɑt]), (adapted from Rapp, 2002; see also Beauvois & Dérouesné, 1981; Caramazza & Miceli, 1989, 1990; Caramazza et al., 1987; Ellis, 1982; Goodman & Caramazza, 1986).

When the system is presented with a string of sounds, *acoustics-to-phonology conversion* processes convert these sounds into a phonological representation. This phonological representation is then processed by lexical and/or sublexical procedures. The *lexical system* becomes activated when the sound stream corresponds to a familiar word, such as “*yacht*”. First, the *phonological lexeme* of the word is accessed in the *phonological input lexicon*, the long-term memory store of the phonological representations of familiar words. The lexical entry then serves as input to the *lexical-semantic system*, providing access to the meaning(s) associated with the lexical item. This information then serves as input to the *orthographic output lexicon*, the long-term memory store of familiar word spellings, and an abstract representation of the spelling of the word—the orthographic lexeme—is accessed (e.g., *y-a-c-h-t*). It has also been proposed (Patterson, 1986; Schwartz, Saffran, & Marin, 1980) that lexical phonological input representations can directly access representations in the orthographic output lexicon, bypassing the lexical semantic system (but see Caramazza & Hillis, 1991). Sublexical processes may play a role in processing all words and are the only means of processing unfamiliar words (or non-words; e.g., *flope*). In sublexical processing, the phonological representation serves as input to the *phonology-to-orthography conversion*

system, which uses stored information about the relationship between sounds and letters to generate a plausible spelling of the phonemes in the stimulus.¹

The output of both lexical and sublexical LTM processes is an abstract, modality- and effector-independent orthographic representation. Activation of this representation must be maintained during subsequent serial selection of letter shapes (for written spelling) and letter names (for oral spelling). Under the view depicted in Figure 1, the WM component of the system is referred to as the *graphemic buffer* and is responsible both for maintaining the activation of orthographic representations and for making the identity of individual letters available to downstream processes in the correct serial order (see Goldberg & Rapp, 2008; Houghton, Glasspool, & Shallice, 1994). More generally, Caramazza et al. (1986) have proposed that temporary storage is required in those cases where there is a discrepancy between the representational unit sizes of consecutive processes. In the case of spelling, the unit size at the level of the orthographic lexicon is the string of letters comprising a word, while the unit size in the motor production systems is approximately a single letter.² Hence, a WM system is arguably needed to provide an interface between these two systems. Specifically, in written spelling the information provided by the buffer is used by the *letter-shape selection* (allographic conversion system) processes to generate shapes for letters, and in oral spelling, the graphemic buffer provides serially ordered letter information to the *letter-name selection* process to generate names for letters (Rapp & Caramazza, 1997).

In summary, the task of spelling to dictation is assumed to recruit a large number of cognitive processes and structures, some of which are specific to spelling (the orthographic lexicon) while others are not (the lexical semantic system); furthermore, some correspond to the LTM repository of learned structures and processes (the orthographic lexicon and phoneme-to-grapheme conversion) while others are dedicated to temporary storage and processing (the graphemic buffer).

The WM/LTM distinction: Neuropsychological evidence

Neuropsychological evidence has played an important role in elucidating the organization and nature of working memory, and patterns of spared and impaired performance exhibited by individuals with acquired neurological deficits have been used to address questions regarding the relationship between WM and LTM (Baddeley, Papagno, & Vallar, 1988; Shallice & Butterworth, 1977). Baddeley and colleagues (e.g., Baddeley & Logie, 1999) have argued that the two are sufficiently independent that one can observe double dissociations of LTM and WM. Specifically there are individuals with severe verbal WM deficits in the context of intact (Vallar & Baddeley, 1984) or close to intact (Shallice & Warrington, 1970) speech production processes (LTM), while there are others who have fairly intact verbal WM in the face of severe language processing deficits (Baddeley & Wilson, 1993).

The literature on acquired dysgraphia has, in a similar fashion, provided evidence regarding the different components of the cognitive architecture of spelling, as functional lesions to different components of the cognitive architecture (outlined in Figure 1) yield particular performance profiles reflecting the constraints imposed by the representations active at the level of the deficit (Badecker et al., 1990; Beauvois & Dérouesné, 1981; Bub & Kertesz, 1982; Caramazza, 1988; Caramazza & Miceli, 1990; Caramazza et al., 1987; Ellis, 1982,

¹Treiman and her colleagues have shown that the phonology–orthography conversion system is critical to the development of reading and writing systems of literate individuals (Treiman, 2000; Treiman & Bourassa, 2000; Treiman & Kessler, 2007), as well as in the adult reading and writing system (e.g., Treiman & Barry, 2000).

²It is worth noting that the motor system responsible for cursive writing will undoubtedly operate over larger units than a single letter, as evidenced by cursive writing “coarticulation”.

1984; Miceli et al., 1985; Shallice, 1981; see Rapp, 2002 for a review). The current investigation is concerned with the distinction between: (a) the LTM storage of the spelling of lexical items, referred to in the literature as the orthographic output lexicon, and (b) the WM component of the spelling system, referred to as the graphemic buffer. Impairment affecting these two processing systems has been typically associated with distinct error profiles characteristic of damage to long-term memory and working memory systems. The spelling performance for individuals with deficits affecting the level of the orthographic output lexicon—the retrieval/activation of a word’s spelling in LTM—is typically marked by word-level effects (e.g., high-frequency words are spelled more accurately than low-frequency words). These effects are assumed to arise because certain words are more robustly encoded in the orthographic output lexicon and thus are more strongly activated during spelling processes. Additionally, in the case of impairment affecting only the orthographic output lexicon, we expect to see phonologically plausible errors (PPEs; e.g., *table* → *taybel*) as these individuals may rely on the phonology–orthography conversion system to generate a response. The reliance on the phonology–orthography conversion system also allows these individuals to be relatively unimpaired in nonword spelling due to the intact functioning of the phonology–orthography system (Baxter & Warrington, 1997; Beauvois & Dérouesné, 1981; Behrmann & Bub, 1992; Goodman & Caramazza, 1986; Goodman-Shulman & Caramazza, 1987; Hatfield & Patterson, 1983; Parkin, 1993; Sanders & Caramazza, 1990; Weekes & Coltheart, 1996), and these individuals are reported not to show an effect of word length (in letters) on spelling accuracy (e.g., Hillis & Caramazza, 1991; Rapp, Epstein, & Tainturier, 2002). Other error types associated with impairment to the orthographic lexicon involve selecting the wrong lexeme, as in lexical errors (e.g., *table* → *tiger*), semantic errors (e.g., *table* → *chair*), and morphological errors (e.g., *table* → *tables*).

In contrast to the orthographic output lexicon, the graphemic buffer is typically assumed to be a limited-capacity process, which suffers a reduction in its already limited capacity in the event of damage to this level. Individuals with impairment affecting the graphemic buffer often exhibit a characteristic error profile (Caramazza et al., 1987; also see Badecker, 1996; Buchwald & Rapp, 2006; Caramazza & Miceli, 1989, 1990; de Partz, 1995; Jonsdóttir, Shallice, & Wise, 1996; Kay & Hanley, 1994; McCloskey et al., 1994; Miceli et al., 1985; Rapp & Kong, 2002; Sage & Ellis, 2004) including: lower accuracy for letters in longer words (due to the increased difficulty of maintaining activation of the letters in a word); and incorrect responses that consist of “letter errors”, such as letter substitutions (e.g., *table* → *take*), deletions (e.g., *table* → *tabe*), additions (e.g., *table* → *tabale*), exchanges (e.g., *table* → *labte*), and shifts (e.g., *table* → *abtle*). In addition to producing letter errors, individuals with impairment affecting the level of the graphemic buffer exhibit few, if any, lexical, semantic, morphological, or phonologically plausible errors, and spelling performance is not typically affected by lexical frequency or other word-level factors. Additionally, letter errors are often (but see Miceli, Capasso, Benvegnù, & Caramazza, 2004; Schiller, Greenhall, Shelton, & Caramazza, 2001; Ward & Romani, 1998) more common in the middle of words than at the beginning or the end of words (see Wing & Baddeley, 1980, for a similar finding in the spelling errors of neurologically intact individuals), although other patterns have been reported with enough consistency to raise the question of whether or not this is a necessary feature of impairment to the graphemic buffer. In addition, qualitatively and quantitatively similar spelling performance is expected for both words and nonwords, as the graphemic buffer is responsible for maintaining the activation of the output of both lexical and sublexical processes (e.g., see Caramazza & Miceli, 1990; Caramazza et al., 1987; Jonsdóttir, Shallice, & Wise, 1996; McCloskey et al., 1994).

Other deficits associated with selective impairment to other portions of the architecture depicted in Figure 1 have been reported in the literature. For example, Rapp and Caramazza

(1997) reported on two individuals with impairment to the letter shape conversion processes outlined in Figure 1. Although the written spelling these individuals produced contained letter errors (e.g., substitutions), their oral spelling was relatively intact, and length effects were not observed. Further, most of the letter errors were substitutions that were similar to the target letter with respect to the strokes required to produce the letter. Although the production of letter errors is similar to what is observed in cases of impairment to the level of the graphemic buffer, Rapp and Caramazza (1997) found that the substitution errors of two individuals with impairment at the level of the graphemic buffer were not influenced by stroke similarity to the target letter, and that the impairment to the graphemic buffer affected both oral spelling and written spelling performance.

Rethinking orthographic LTM and WM distinctions?

Sage and Ellis (2004) presented data from a dysgraphic individual—coupled with a reanalysis of previous cases of individuals with impairment to the graphemic buffer—that raised questions regarding the traditional distinctions outlined above between impairments to the orthographic lexicon (lexical orthographic LTM) and the graphemic buffer (orthographic working memory). Specifically, Sage and Ellis (2004) pointed out three major inconsistencies between the performance of a dysgraphic individual (B.H.) and the traditional description of deficits affecting the graphemic buffer.

First, they reported that the length effect on B.H.'s whole-word spelling accuracy was greatly diminished on a list comparing five- and eight-letter words matched on various lexical factors including number of orthographic neighbours (Coltheart's *N*; Coltheart, Davelaar, Jonasson, & Besner, 1977), lexical frequency, imageability, and age of acquisition (from Lavidor & Ellis, 2002). They argued that length effects—one of the hallmarks of a deficit affecting the level of the graphemic buffer—may appear exaggerated as an artefact of differences in lexical variables that are not traditionally controlled in comparing words of different lengths (particularly *N*). Second, a multiple regression analysis revealed that each of those lexical variables was a significant predictor of B.H.'s spelling accuracy. This result led Sage and Ellis (2004) to examine the previous literature on deficits affecting the graphemic buffer, reviewing several possible cases of lexical influences on the performance of individuals fitting the profile of graphemic buffer deficit. On the basis of these lines of evidence, Sage and Ellis proposed that lexical influences in the spelling performance of individuals with impairment to the graphemic buffer arise naturally from different activation levels of letters held in the graphemic buffer for words that are more or less robustly represented in the semantic system and the lexicon (i.e., words with high vs. low lexical frequency, imageability, *N*; early vs. late acquired words). We return to this issue in the General Discussion (also see Glasspool, Shallice, & Cipolotti, 2006, for a formally explicit proposal along these lines).

Third, in addition to addressing issues related to effects of word length and lexical variables in individuals with impairment to the graphemic buffer, Sage and Ellis (2004) also used B.H.'s performance to question the bow-shaped serial position accuracy function, in which letters at the beginning and ends of words are produced more accurately than those in the middle of words (Buchwald & Rapp, 2006; Caramazza & Miceli, 1990; Jonsdottir et al., 1996; McCloskey et al., 1994; Tainturier & Rapp, 2004; but see Miceli et al., 2004; Schiller et al., 2001; Ward & Romani, 1998). The reason for this bow-shaped accuracy function (also observed in neurologically intact individuals, Wing & Baddeley, 1980) is not well understood and may or may not have the same basis as similar functions reported in verbal working memory tasks (Deese & Kaufman, 1957; Murdock, 1962; see Glanzer & Cunitz, 1966, and Atkinson & Shiffrin, 1968, for discussion). Sage and Ellis noted that many case reports of individuals with hypothesized damage affecting the graphemic buffer that have examined effects of serial position on letter accuracy limit the analyses to those responses

that deviate from the target by a single letter. They pointed out that, if that is the case and if a dysgraphic individual commits a large number of errors consisting of partial responses, these would be excluded from the analysis. Under those circumstances, the error rate at the ends of words would appear lower than if all responses are considered. As an example, Sage and Ellis reported that B.H. frequently produced incomplete responses for words being produced (e.g., *algae* → ALG; *false* → F). Thus, they raised the possibility that, at least in certain cases, the bow-shaped accuracy function may be an artefact of limiting position-based error analyses to words with only one letter error (see Glasspool et al., 2006, for a different interpretation of this pattern).

Additional challenges to the traditional distinction between orthographic LTM and WM come from other cases that do not fall readily into one category of deficit or the other, as they exhibit mixtures of the symptoms from both (Cipolotti, Bird, Glasspool, & Shallice, 2004; Glasspool et al., 2006). Cipolotti et al. (2004) posited functional impairment containing elements of both deep dysgraphia and graphemic buffer impairment (also see Glasspool et al., 2006). They claimed that individuals with this deficit exhibit the hallmarks of impairment to the graphemic buffer (e.g., length effects, single letter errors, etc.) as well as some lexical effects on spelling performance. In addition, the spelling errors of these individuals also contain a substantial number of semantic and lexical errors, one of the hallmarks of deep dysgraphia. Glasspool et al. (2006) reported computational analyses indicating that this pattern may be observed in the absence of impairment to the graphemic buffer. As with Sage and Ellis (2004), although these authors do not specifically question the distinction between orthographic LTM and orthographic WM, the data patterns they report prompt a reexamination of whether it is necessary to posit both LTM and WM components in the spelling system.

In the following sections, we present a series of four case studies of dysgraphic individuals. For each of these individuals, we present results of analyses designed to assess effects of length and lexical variables, as well as letter accuracy as a function of within-word serial position. In addition to this primary theoretical focus of the paper we also present arguments and empirical evidence regarding the methodological issue that concerns use of letter versus word accuracy as a diagnostic for orthographic WM impairments. With regard to the LTM and WM distinction, our key empirical findings confirm the distinction between long-term memory and working memory components of the spelling system while providing indications of the interactions between these systems. These findings have implications beyond our understanding of the spelling system, to the broader ongoing debate regarding the nature of the relationship between LTM and WM.

CASE REPORTS

In this section, we first provide a general profile for each of the 4 participants in this study (see Table 1 for a summary) and then go on to focus specifically on their spelling performance. The language data reported primarily involve assessments of written and spoken language production and comprehension at the level of the single word. For each participant, the data reported in this investigation were collected considerably after the cerebrovascular accident (CVA), at a time when performance was very stable. Some details of the performance of these individuals have been reported elsewhere, and in those cases the reader is referred to the reports in the literature for more detailed information.

B.W.N

B.W.N. (also reported in Buchwald & Rapp, 2006; Tainturier & Rapp, 2004) was a right-handed man who suffered two CVAs, 9 and 5 years prior to the onset of this investigation. He held a PhD and had worked as a teacher, a high-level school system administrator, and

was president of the city chapter of a prestigious public affairs organization. Prior to his CVAs, B.W.N. was an excellent public speaker and speller, and premorbid writing samples contained no errors. While in school, B.W.N. was a finalist in regional spelling competitions, and copies of editorials and letters to local newspapers reveal a man who was particularly gifted in written expression. Computed tomography (CT) scans indicate an older left parietal lesion and a more recent right parietal lesion. The left hemisphere lesion is the larger of the two, extending in the inferior–superior dimension from the superior temporal gyrus to the superior parietal gyrus and, in the anterior–posterior dimension, from the postcentral gyrus to the angular gyrus. The right hemisphere lesion affected the posterior parietal lobe, including the angular and superior parietal gyri.³

As a result of his strokes, B.W.N. suffered mild right-sided weakness and loss of somatosensation in the right hand, but he showed no evidence of visuospatial neglect. He suffered moderate difficulty in spoken language production, primarily characterized by word-finding difficulties and phonological errors with an accuracy of 68% (177/260) in spoken picture naming of line drawings from the Snodgrass and Vanderwart (1980) set. He suffered mild hearing loss and had some auditory discrimination difficulties as measured by the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA; Kay, Lesser, & Coltheart, 1992) auditory word discrimination test, 89% (64/72; norm: mean correct = 70.4, *SD* = 3.4) and PALPA auditory nonword discrimination 90% (65/72; norm: mean correct = 70.8; *SD* = 2.9). Nonetheless, B.W.N.'s auditory word and sentence comprehension were very good, scoring in the 94th percentile on the Peabody Picture Vocabulary Test–Revised (PPVT–R, Dunn & Dunn, 1981) and 94% (15/16) correct in matching auditorily presented reversible sentences with pictures. B.W.N.'s written comprehension was also excellent, as he scored 100% correct in synonym matching for abstract and concrete words and 99% correct (139/140) in visual lexical decision; furthermore, he continues to read the newspaper for pleasure, although not as easily as he did prior to the CVAs.

R.S.B

R.S.B. (also reported in Buchwald & Rapp, 2006; Rapp, 2005; Rapp & Kane, 2002; Rapp & Kong, 2002) was a right-handed man who suffered a CVA in 1996 at the age of 54, 5 years prior to the onset of this investigation. Magnetic resonance imaging (MRI) scans reveal a lesion in the left anterior parietal region, extending from the post-central gyrus to the angular gyrus. R.S.B. held a PhD and had worked as a toxicology researcher prior to the CVA; he had published several articles and reported no premorbid spelling difficulties. Premorbid samples in the form of handwritten toxicology work reports were analysed, with errors on only 0.4% of the words in the sample (7/1,624). He was a bilingual speaker of English and Spanish, although he had almost exclusively spoken English since age 15. Although the CVA forced his early retirement, he remained able to drive, read for pleasure, and manage family affairs. However, R.S.B. suffered from word-finding difficulties in spontaneous speech, correctly naming only 75% of pictures (161/215) in a confrontation naming task involving the Snodgrass and Vanderwart (1980) picture set. R.S.B. also had mild auditory discrimination difficulties (PALPA No. 2 word discrimination: 62/72, 86%; PALPA No. 1 nonword discrimination: 68/72, 94%). Despite the mild word-finding and auditory discrimination impairments, R.S.B.'s single-word auditory comprehension was excellent; his performance was perfect (260/260) on an auditory word/picture verification task, he scored in the 97th percentile (173/175) on the PPVT–R (Form L), and he was 100% (16/16)

³B.W.N. began participating in research two years after the left hemisphere CVA, which gave rise to the symptoms that are reported here. He continued to be tested after the second CVA, which affected the right hemisphere, at which time retesting was carried out to determine whether his performance had significantly changed. While there was a temporary worsening of symptoms, B.W.N.'s pattern of spared and impaired performance as well as the distribution of his error types remained constant.

correct in matching auditorily presented reversible sentences with their corresponding pictures. R.S.B.'s written language comprehension was also excellent with accuracy of 99% (180/182) in visual lexical decision.

D.H.Y

D.H.Y. was a right-handed male who suffered a CVA in August 2002, at the age of 35, and 2 years before the onset of this investigation. Prior to the CVA, D.H.Y. obtained a B.A. in Economics and had been employed as a banker and marketing consultant. The CVA produced moderate spoken- and written-language difficulties. Though no longer able to perform the requirements of his previous employment, D.H.Y. continued to drive, work, read, and live an independent life. The CVA resulted in a large left hemisphere lesion, affecting the posterior inferior frontal gyrus, the inferior portion of the postcentral gyrus, the supramarginal gyrus, the superior and middle portions of the angular gyrus, and the superior edge of the superior temporal gyrus. D.H.Y.'s auditory discrimination for words (97%, 70/72) was within the normal range, with only slightly impaired performance for nonwords (92%, 66/72). Further, his single-word auditory comprehension was excellent as assessed using the PPVT-R, where D.H.Y. scored in the 87th percentile. Auditory sentence comprehension was also fairly intact with a score of 88% (14/16) on a sentence/picture matching test involving reversible sentences. D.H.Y. experienced moderate difficulties producing sentences in spontaneous speech, exhibiting some marked hesitations and word-finding difficulties, though he made no semantic errors, and his single-word picture naming was 100% correct (35/35) on the Birmingham Object Recognition Battery (BORB; Riddoch & Humphreys, 1993) picture naming task, despite occasional slowness. Furthermore his written-word comprehension was excellent as indicated by his score of 98% correct (117/120) on the PALPA No. 25 visual lexical decision task.

V.B.R

V.B.R. (also reported in Buchwald, 2005; Buchwald, Rapp, & Stone, 2007), was a right-handed woman, with a high-school degree who suffered a CVA at the age of 51, 6 years prior to the onset of the current investigation. MRI scans revealed a large left hemisphere fronto-parietal infarct involving posterior frontal lobe, including Broca's area, pre- and postcentral gyri, and the supramarginal gyrus. V.B.R. had a right hemi-paresis as a result of the CVA; she occasionally used support to walk and lost the use of her right arm below the elbow. The CVA also induced strabismus, which she wore lenses to correct. Prior to her CVA, V.B.R. was the president of a small company and was an avid reader. Although the CVA forced her early retirement, V.B.R. remained able to drive and to read short articles in the newspaper.

V.B.R.'s language production skills were severely impaired as a result of the CVA. Sentence production was virtually impossible, and single-word picture naming was 64% correct (21/33) and characterized by marked hesitations and phonemic errors; V.B.R. made no semantic errors in picture naming. In marked contrast to her poor production, her word comprehension was quite good. On the PPVT-R (Dunn & Dunn, 1981) she scored in the 75th percentile, and she correctly matched 88% (14/16) pictures to reversible sentences that were presented auditorily. Further, V.B.R.'s nearly flawless performance on the PALPA minimal pair discrimination tasks for words (99%, 71/72) and nonwords (99%, 71/72) revealed the absence of a perceptual deficit in spoken-word recognition. Her written-word comprehension was excellent with 100% accuracy on written synonym judgements and 100% in visual lexical decision (PALPA No. 25).

In sum, all 4 participants were right-handed, highly literate individuals who suffered language deficits subsequent to CVAs. The 4 participants all suffered from some degree of

spoken production difficulty, ranging from mild to severe. In contrast, they were all generally intact in both written- and spoken-word comprehension, with performance ranging from very good to excellent. The subsequent sections provide detailed evaluations of their spelling abilities.

A methodological note on the assessment of spelling performance

Prior to presenting the spelling performance of these individuals, it is important to note that we assess these individuals' spelling performance by analysing the proportion of letters produced correctly rather than the proportion of words produced correctly. In our view, this is critical to the task of determining the locus of impairment within the spelling system; we believe that only letter accuracy (and not word accuracy) can adequately distinguish a deficit affecting a limited-resource graphemic WM system from one affecting other components of the spelling system. Under conditions of damage, as the amount of information that has to be maintained active by a limited-resource working memory system is increased, we should expect a higher probability of error per letter. This is not necessarily the case for deficits to other components of the spelling system, which may show a length effect on word accuracy, but not on letter accuracy.

To illustrate this point, consider first a deficit affecting the allographic conversion system, which converts the abstract letter identities maintained active in the buffer to letter shapes. Let us assume that the deficit is such that there is a probability of .25 of selecting an erroneous letter shape for each letter to be spelled (and thus a .75 probability of spelling each letter correctly). At this rate, *word* accuracy for four-letter words should be approximately 31.6% $[(0.75)^4]$; the chance of getting each letter correct], but only about 10.0% $[(0.75)^8]$ for eight-letter words. Nevertheless, *letter* accuracy should remain at 75% for words of each length. Thus, there is the possibility of an effect of length on word accuracy and not on letter accuracy in the case of impairment affecting the allographic conversion process.

A similar issue arises in distinguishing cases of impairment affecting the graphemic buffer from impairment affecting the orthographic output lexicon. In the case of a lexical deficit, spelling may rely on proper functioning of the phonology–orthography conversion system. However, because English does not have a transparent orthography, it is frequently not possible to accurately spell words just by knowing phonology-to-orthography mappings. Furthermore, it is likely that longer words are more likely to contain sequences with irregular mappings from phonology to orthography simply because they contain more phonemes. In that case, longer words would have more opportunities for error, even if the error rate per phoneme–grapheme mapping were constant. In contrast, damage to the graphemic buffer (if it is indeed resource limited) should necessarily lead to a length effect on letter accuracy, as longer words place greater demands on a limited resource buffer, leading to an increase in the probability that a letter will be spelled incorrectly when it is in a longer word compared to a shorter word. We will return to this issue in our discussion of Table 5, which reports spelling performance on a list that contrasts length while controlling for lexical factors such as frequency, *N*, and age of acquisition (AoA).

Localizing the deficits in the spelling system

The spelling performance discussed here come from spelling-to-dictation tasks in which participants are auditorily presented with words, which they then repeated (to ensure the correct word was heard) and spelled. All spelling tasks were written spelling unless otherwise indicated. For each of the individuals we examined, we attempted to identify the locus of the deficit in the spelling system. To do so, we administered the Length List of the Johns Hopkins University (JHU) Dysgraphia Battery (Goodman & Caramazza, 1985) to

each of the participants. This list contrasts high- and low-frequency words ranging from 4 to 8 letters in length. For the purposes of the present study, this list is helpful in providing a basic error profile for these individuals. The performance of these individuals on the Length List is presented in Tables 2 and 3, with Table 2 presenting the contrast between high-frequency words with low-frequency words and Table 3 comparing performance on short words (4 and 5 letters) with longer words (7 and 8 letters).⁴

The results presented in these two tables show that B.W.N. and R.S.B. exhibit the typical pattern associated with impairment affecting orthographic working memory. These two individuals exhibit no effect of frequency on spelling accuracy (Table 2) and a significant effect of letter length (Table 3). D.H.Y. and V.B.R. exhibit the opposite pattern, with significantly better performance for high-frequency words than for low-frequency words (Table 2) and no significant difference in performance based on length (Table 3).

It is also important to evaluate whether there are deficits earlier in the cognitive spelling system (i.e., the phonological input lexicon or the lexical semantic system) or later in the processing stream (i.e., letter shape and letter name conversion systems). With respect to the phonological input lexicon and semantic system, each individual performed very well in tasks that require accurate processing of auditory presented words (see Table 1); thus, the evidence indicated that these systems were not the source of impaired spelling performance for these individuals.

Deficits arising from the letter shape and letter name conversion systems would have the following consequences: an absence of an effect of length on letter accuracy; letter errors should be produced; and there should be a discrepancy between written and oral spelling accuracy. None of the 4 participants fits the pattern of a letter name or shape conversion deficit. With regard to D.H.Y. and V.B.R., although the absence of a length effect could be consistent with a postbuffer deficit, their pattern of errors is problematic for such a conclusion. Table 4 reports the distribution of error types for each of the individuals in the study, including all data considered throughout this paper. It is clear from Table 4 that D.H.Y. and V.B.R. each exhibit a strong tendency towards phonologically plausible errors and lexical errors, neither of which are expected from a deficit affecting these postbuffer conversion systems.

With regard to B.W.N. and R.S.B., a postbuffer locus of impairment can be ruled out because, as already indicated in Table 3, each of these individuals exhibits a clear effect of length on letter accuracy. Furthermore, they show similar performance for oral and written spelling on administrations of the Length List from the JHU Dysgraphia Battery (Goodman & Caramazza, 1985). B.W.N.'s letter accuracy was 95% for both oral spelling (397.5/420) and written spelling (400/420). R.S.B. shows worse performance on oral spelling (337/420, 80%) than on written spelling (392/420, 93%; $\chi^2 = 30.21, p < .01$). In his case, therefore, an additional mild deficit in letter naming cannot be ruled out. However, this will not affect the analyses and conclusions reached in this paper as the data reported for each individual in this paper come from written spelling tasks.

⁴The scoring procedure regarding letter accuracy used for the analyses in this paper follows that detailed in Caramazza and Miceli (1990). Each target position in a word can receive a total of 1 point when the correct letter is produced in the correct location. If a letter is present but in the wrong position (e.g., the "D" in *word* → *WDOR*, it receives half a point. For double letters, if one letter is deleted (*rabbit* → *RABIT*), each position loses half a point. Further, an error was classified as a phonologically plausible error (PPE) if it was possible for the sounds in the word to be spelled with the letters produced. For example, a response of "MAK" would be considered a PPE for the target of *make* because "A" is one possible spelling of the phoneme /e/ (as in *baby*).

With respect to Table 4, once again we see a clear distinction between B.W.N. and R.S.B. on one hand and D.H.Y. and V.B.R. on the other, in this case in terms of the types of errors produced.

The errors from the first two individuals overwhelmingly (67–88%) result in nonwords (e.g., *table* → *tible*). They each produce primarily letter errors (B.W.N.: 38% deletions; 33% substitutions; 20% movement; 9% insertion; R.S.B.: 62% deletions; 24% substitutions; 8% movement; 6% insertion). Further, both B.W.N. and R.S.B. produce very few of the types of errors expected from damage to the lexical system: PPEs, morphological errors, semantic errors, or other orthographically similar word errors (e.g., *breed* → *bread*). Moreover, of the errors that they do produce that correspond to words or phonologically plausible spellings, most result from a single letter error (e.g., *virtue* → *vertue*) that could have come about as a result of a buffering failure (single letter errors/total errors: B.W.N.: 84%, 96/114; R.S.B.: 77%, 99/129). In contrast, the errors of D.H.Y. and V.B.R. are much more likely to be PPEs and morphological, semantic, or other word errors, and these are less likely to result from a single letter error (D.H.Y.: 26%, 20/77; V.B.R.: 24%, 11/46). Neither of these individuals made a substantial number of fragments (defined as a deletion of the last three or more letters of a word; D.H.Y.: 3%, 4/130; V.B.R.: 3%, 2/67).

With respect to the nonword spelling performance of these individuals, we have somewhat limited data. Each individual spelled nonwords less accurately than words, although the overall pattern of nonword spelling was consistent with the underlying deficit. Each individual spelled non-words from the Part-of-Speech list of the JHU Dysgraphia Battery (Goodman & Caramazza, 1985). B.W.N. spelled 11/29 nonwords (38%) correctly, with a letter accuracy of 81%. As with word spelling, his errors largely consisted of single-letter errors (e.g., /gɜb/ → *gerd*), and included only 1 lexicalization (/fin/ → *fiend*; 3% of errors). R.S.B. spelled 19/31 nonwords (68%) correctly, with a letter accuracy of 88%. As with B.W.N., R.S.B.'s incorrect spellings were marked by single-letter errors (e.g., /tʃentʃ/ → *chence*), with only 1 lexicalization (/bok/ → *bout*; 8% of errors). These patterns are consistent with the hypothesized deficits to orthographic working memory.

The nonword spelling of D.H.Y. and V.B.R. reveals additional problems with phoneme–grapheme conversion. Of 26 nonwords, D.H.Y. did not correctly spell any items, with 57% letter accuracy. His errors included 6 lexicalizations (e.g., /bok/ → *both*; /wes,l/ → *well*; 23% of errors). V.B.R. produced 4/34 nonwords (12%) correctly, with 68% letter accuracy, with 5 lexicalizations (e.g., /mɜbɜ/ → *mirror*; 17% of errors).

In sum, the performance of these individuals indicates a divide between B.W.N. and R.S.B.—whose performance is consistent with impairment to the WM component of the spelling system—and D.H.Y. and V.B.R., whose performance is consistent with impairment to the LTM component of the spelling system. In the following sections, we present further evidence suggesting a functional divide in the performance of these two sets of individuals, and we more systematically explore the factors that affect the spelling accuracy for each of these individuals.

Analysis 1: Effect of length on spelling accuracy

Sage and Ellis (2004) reported that the effect of letter length on the spelling accuracy of B.H., an individual with impairment affecting the graphemic buffer, was attenuated when five- and eight-letter words were matched on lexical frequency, imageability, orthographic neighborhood size (*N*), and age of acquisition (five-letter words: 11/48; eight-letter words: 16/48; $\chi^2 = 0.82$; note that letter accuracy was not reported). They interpreted this result as evidence that the effect of letter length on spelling accuracy in cases of impairment affecting the graphemic buffer may have been exaggerated due to conflation of length and certain

lexical variables, particularly *N*. We concur with Sage and Ellis that it is important to attempt to isolate the effect of length from the effects of other variables that may correlate with length. However, we argue here that the list administered by Sage and Ellis to B.H. contained a systematic bias, which should lead to better performance on longer words than shorter words and, in so doing, would have masked the length effects. In the list Sage and Ellis presented to B.H. (from Lavidor & Ellis, 2002), 30/48 eight-letter words were morphologically complex (e.g., *football*, *goodness*) whereas none of the 48 five-letter words were transparently morphologically complex. As Badecker et al. (1990) and Badecker, Rapp, and Caramazza (1996) argued, constituent morphemes may be processed separately in the course of spelling. If so, this would reduce the load on the graphemic buffer. Thus, the systematic difference in morphological complexity of the long and short words potentially weakens Sage and Ellis' claim.

To address this issue, each of the 4 participants was presented with a modified version of the Lavidor and Ellis (2002) list, in which no words of either length were morphologically complex. In the revised list, five-letter words are matched with eight-letter words on lexical frequency (from Kucera & Francis, 1967), *N* (computed over the Kucera & Francis database), age of acquisition, and imageability (from Medical Research Council, MRC, Psycholinguistic Database; Coltheart, 1981). Table 5 presents the spelling performance on this revised list for each participant.

Several issues are raised by the data presented in Table 5. First, focusing on the left side of Table 5, we find evidence that contrasts with Sage and Ellis' (2004) claim that length effects on accuracy may be an artefact of uncontrolled lexical variables (primarily *N*). Rather, for B.W.N. and R.S.B. we see a robust effect of length on spelling accuracy on a list whose words are matched for lexical variables. In contrast, neither D.H.Y. nor V.B.R. exhibit significant differences between five- and eight-letter words when the words are matched for frequency, imageability, age of acquisition, and *N*. These results are consistent with the claim that B.W.N. and R.S.B. have impairment affecting the working memory system involved in spelling whereas D.H.Y. and V.B.R. do not.

The data reported in Table 5 also provide a striking example of the importance of using letter accuracy—and not word accuracy—as the dependent variable in assessing spelling performance. In particular, if we only examined word accuracy (right-hand shaded side of the table), we would observe that all four of these individuals exhibit significant effects of length, with longer words spelled less accurately than shorter words. However, a significant effect of length on letter accuracy is observed only for B.W.N. and R.S.B. As discussed above, we may see length effects when measured by word accuracy for a variety of reasons, and it may be an inappropriate diagnostic of a buffer-related length effect. It is worth noting here that Sage and Ellis (2004) report B.H.'s spelling performance based on word accuracy only; letter accuracy data were not reported, so evaluation of B.H. with respect to this criterion is not possible.

In addition to the revised list discussed above, each participant was administered the original Lavidor and Ellis (2002) list that Sage and Ellis (2004) administered to B.H. The results of these administrations are presented in Table 6. Crucially, for analyses with word accuracy as the dependent variable, none of the individuals we examined exhibited a significant effect of length on their spelling performance. Thus, with respect to B.W.N. and R.S.B., we find that these individuals, who otherwise present with the characteristics of graphemic buffer impairment, exhibit similar performance to B.H. on this list. It is also worth noting that R.S.B.—whose performance on all other spelling tasks indicates impairment affecting the graphemic buffer—does not show a significant effect of length on letter accuracy on this list. We believe that this result highlights the aforementioned problem with having a large

number of morphologically complex words among the eight-letter words and a relatively small number of such words among the five-letter words.

In summary, Analysis 1 addressed the Sage and Ellis (2004) claim that the length effect in individuals with impairment affecting the graphemic buffer may be confounded by certain lexical properties of longer words (e.g., lower *N*). We administered a list that controlled for several critical lexical variables—including morphological complexity—to each of the individuals in this study and found a clear distinction: B.W.N. and R.S.B. exhibited significant effects of length on spelling accuracy whereas D.H.Y. and V.B.R. did not exhibit length effects. This supports the long-standing assertion that there exist distinct patterns of performance in the case of spelling deficits, which differ with respect to sensitivity to the length of the target stimulus.

Analysis 2: Accuracy as a function of serial position in word

In this section, we examine accuracy as a function of the position of letters in a word. Impairment affecting the graphemic buffer has been typically associated with a bow-shaped accuracy function, such that individuals perform better at letters at the beginning and end of words than they do on medial letters (Buchwald & Rapp, 2006; Caramazza & Miceli, 1990; Jónsdóttir et al., 1996; McCloskey et al., 1994; Tainturier & Rapp, 2004; but see Miceli et al., 2004; Schiller et al., 2001; Ward & Romani, 1998). Sage and Ellis (2004) raised the possibility that this pattern may be an artefact of limiting analyses to errors that consist of single letters, which eliminates partial responses from these analyses (e.g., *false* → F), a practice that would tend to increase accuracy in the later positions in the words.

For the analyses in Figure 2, we have included performance on all words on which these individuals were tested. To compare words of different lengths, we have normalized the letter positions of words using the procedure outlined in Machtynger and Shallice (2009; an update of the Wing and Baddeley, 1980, scheme). As can be seen in Figure 2, letter accuracy for B.W.N. and R.S.B. varies across letter position in the bow-shaped manner that has been reported for a number of individuals with deficits affecting the graphemic buffer. Notably, this contrasts with the spelling performance of D.H.Y. and V.B.R.; for each of these individuals, there are as many or more errors for each successive position in the word. These data indicate that, for B.W.N. and R.S.B., the bow-shaped accuracy function for accuracy across serial position is not an artefact of limiting the errors used in the analysis.

Most of the spelling errors for B.W.N. and R.S.B. consist of single-letter substitutions and deletions. When we looked at the substitution errors separately and the deletion errors separately, the same pattern emerged as that seen in Figure 2; in particular, there were both more substitutions and more deletions in the middle of words than at the beginning or the end.

One possible concern is that the bow-shaped accuracy function could reflect the fact that letters in the middle of words are somewhat less regular in their phoneme–grapheme correspondence (PGC). If that were the case, and if there were lexical deficits, then one might expect these particular segments to have multiple opportunities to be produced in error (see also Jones, Folk, & Rapp, 2009). To address this concern, we first computed the PGC probability for each letter in the word list given in Table 5, based on Hanna, Hanna, Hodges, and Rudorf (1966). We then looked at only those letters with a PGC probability of greater than .8 (i.e., that sound is spelled with that letter at least 80% of the time). By identifying these high PGC probability letters, we were able to create a subset of letters that have equivalent PGC probabilities at each serial position (normalized according to the procedure proposed by Wing & Baddeley, 1980). For each serial position, the mean PGC probability was between .93 and .96: Position A, .94 (*SD* = .04); Position B, .96 (*SD* = .04);

Position C, .96 ($SD = .04$); Position D, .93 ($SD = .06$); Position E, .94 ($SD = .04$). Given that these letters have the same PGC probability at each serial position, if the bow-shaped serial position effect is obtained for these letters, then this provides strong evidence that this effect is not simply an artefact of differing PGC probabilities at different positions within a word.

The results of this analysis are presented in Figure 3. The bow-shaped serial position effect is clearly maintained for the 2 individuals who exhibit a deficit consistent with impairment affecting the level of the graphemic buffer, providing clear evidence that this feature is not reducible to a PG probability effect but, instead, reflects the (not well-understood) forces that influence the robustness of information held in orthographic WM. The data in Figure 3 also indicate that D.H.Y. and V.B.R. do not show this pattern, particularly with respect to the final serial position, which is less accurate than the fourth position for each of these individuals. Thus, the bow-shaped pattern showing better performance at the beginning and end of words is limited to the individuals fitting the pattern of impairment affecting the graphemic buffer.

Analysis 3: Effects of lexical variables: Frequency, age of acquisition, imageability, and N

Thus far, we have seen that the participants separate cleanly into two groups: B.W.N. and R.S.B. have exhibited the length effects and bow-shaped accuracy functions associated with graphemic buffering impairment, while V.B.R. and D.H.Y. have not exhibited these characteristics but have, instead, exhibited sensitivity to the lexical factor of word frequency. In this section, we carry out a more detailed examination of the influence of lexical variables. Whereas the traditional description of the graphemic buffer claims that this process should be insensitive to lexical factors (Caramazza et al., 1987; Miceli et al., 1985), Sage and Ellis (2004) recently reported that (at least some) individuals with impairment affecting the graphemic buffer display sensitivity to lexical variables in their spelling performance (both in their case report of B.H. as well as in a review of a series of individuals reported to have damage affecting the level of the graphemic buffer).

In this section we present three sets of results. First, we combine data across all lists administered for each individual and evaluate the effect of a number of variables. This analysis has the advantage of including a large amount of data, but the categories that are compared are not specifically matched on other potentially relevant variables. In this way it provides an overview of the data. We then follow this up by two sets of controlled analyses. In the first we consider two word lists designed to factorially test the influence on spelling accuracy of lexical frequency and age of acquisition (following Sage & Ellis, 2004). We then report on individual multiple regression analyses that allow us to examine these two factors as well as length, N , and imageability.

Analysis 3a: Overall effects of lexical variables—For each individual, we used the entire pool of stimuli administered for spelling to dictation and extracted stimuli that allowed for the following comparisons—length: short (4–6 letters) versus long (7–9 letters); frequency: high frequency (>15 in Kucera & Francis, 1967) versus low frequency (<10); N : high N ($N > 1$) versus low N ($N \leq 1$); imageability: high imageability (≥ 450) versus low imageability (≤ 350) words (from the MRC Psycholinguistic Database; Coltheart, 1981); and AoA, with early-acquired (≤ 350) versus late-acquired (≥ 450) words. The analyses of imageability and AoA require a particular note of caution; these analyses are less reliable than the others as ratings for these measures were available for only a small percentage of the words in this list.

The results are presented in Table 7. These results confirm two critical distinctions that have been noted. First, with respect to effects of word length on spelling accuracy, we see that length affects the performance of the two individuals with hypothesized impairment to the

graphemic buffer (B.W.N. and R.S.B.) but not to the two individuals with hypothesized impairment to the orthographic lexicon (D.H.Y. and V.B.R.). This result provides further support for the distinction between these two groups of individuals, as well as the distinction between WM and LTM components of the spelling system.

The results indicate that D.H.Y. and V.B.R.'s spelling performance is sensitive to all of the lexical variables. In addition, the data also indicate—consistent with Sage and Ellis's (2004) claims—the effect of certain lexical factors on the performance of at least some individuals with graphemic buffering impairment. In particular, B.W.N. performs better on high-frequency words than on low-frequency words and on early-acquired words than on late-acquired words. R.S.B. performs better on high-frequency words and high *N* words than on their low counterparts, and he performs better on early-acquired words than on late-acquired words (e.g., Ellis & Lambon Ralph, 2000; Zevin & Seidenberg, 2002).

Analysis 3b: Factorial comparisons: Frequency and age of acquisition—The first list, from Morrison and Ellis (1995), contains four groups of words that vary in frequency and age of acquisition: early acquired, high frequency; early acquired, low frequency; late acquired, high frequency; and late acquired, low frequency. Unfortunately, Morrison and Ellis did not match all four groups of words on letter length; letter length is only controlled for across the two sets of early acquired words and the two sets of late acquired words. Thus, these lists can be used to assess the effect of frequency within each AoA group, but not to evaluate the effect of AoA itself.

The results are presented in Table 8. The data indicate that both D.H.Y. and V.B.R. exhibit significant effects of lexical frequency on their spelling of both early-acquired and late-acquired words. These data are consistent with their performance on other lists that have consistently revealed effects of lexical variables. In contrast, for B.W.N. and R.S.B., there was no significant effect of lexical frequency.

The second list we report, from Gerhard and Barry (1998), contrasted lexical frequency and age of acquisition (AoA) of words 4–6 letters in length. This list allowed for two comparisons. Two subsets consisted of early-acquired and late-acquired words that were matched for letter length and frequency. Several lines of computational and empirical evidence suggest that early-acquired words should be more robustly represented in the lexicon (Ellis & Lambon Ralph, 2000; Zevin & Seidenberg, 2002) and are thus less prone to disruption in the case of a deficit affecting the lexicon. Two other subsets of words consisted of high- and low-frequency words that were matched for letter length and AoA. We present the results from testing each of these contrasts separately.

On the portion of the list comparing early- and late-acquired words (results shown in Table 9), only D.H.Y. exhibited a significant effect of AoA on spelling performance. This result is consistent with a deficit affecting the long-term memory component of the spelling system. It is worth noting that V.B.R.'s performance was near ceiling in each category. Thus, this list may not be sensitive enough to determine whether V.B.R.'s performance is sensitive to AoA. The accuracy levels exhibited by B.W.N. and R.S.B. all indicate that AoA had no significant effect on their spelling performance.

On the other portion of the Gerhard and Barry (1998) list (presented in Table 10), D.H.Y., V.B.R., and R.S.B. exhibited significant effects of lexical frequency on words matched in AoA and letter length. For D.H.Y. and V.B.R., these results are consistent with the previous lists on which they exhibited sensitivity to lexical factors and not to letter length. The fact that R.S.B. exhibits a significant frequency effect may not be entirely surprising, as on many of the previous lists both R.S.B. and B.W.N. have exhibited non-significant trends towards

better performance on the words that are presumed to be more robustly encoded in the lexical LTM system—the early-acquired words (Table 8) as well as the high-frequency (Table 9) words.

Analysis 3c: Multiple regression analyses—For each of the 4 individuals in this study, we performed two multiple regression analyses including all stimulus words reported in this paper. The analyses were performed with letter accuracy as the dependent variable and independent variables of the following: length in letters; frequency (from Kucera & Francis, 1967); *N* (orthographic neighbourhood computed over Kucera & Francis); and imageability and AoA (both from MRC psycholinguistic database). The two analyses were a stepwise regression and a regression in which every variable other than length was first entered into the equation, and then length was added as a regressor to determine whether it added to the prediction above and beyond that of the other variables. The degree of intercorrelation among these variables was assessed independently for each individual's data set.

For B.W.N., the regression model accepted length, frequency, and AoA as significant predictors. Length was the first independent variable accepted as a significant predictor, $F(1, 485) = 39.072, p < .001$, with an R^2 change of .075 (total adjusted R^2 for model with one factor = .073). The next predictor accepted by the model was frequency, and the change was significant $F(1, 484) = 4.90, p < .03$, with an R^2 change of .009 (total adjusted R^2 for model with two factors = .080). AoA was the third and final significant predictor accepted by the model, $F(1, 483) = 14.21, p < .01$, with an R^2 change of .026 (total adjusted R^2 for model with three factors = .104). The correlations among the independent variables ranged from .02 to .57. To verify that length was a significant predictor above and beyond the lexical variables, we entered each of the four lexical variables into the regression equation first and then added length as a regressor. This analysis also indicated that length was a significant predictor, $F(1, 481) = 24.36, p < .001$, with an R^2 change of .044. The finding that length was a significant predictor was consistent with B.W.N.'s pattern of results observed throughout this work. The addition of two lexical factors is unexpected with respect to the traditional description of orthographic WM, but is consistent with the data presented in Analysis 3a.

For R.S.B., the regression model accepted length, frequency, and *N* as significant predictors. The model first accepted length as a significant predictor, $F(1, 370) = 55.49, p < .001$, with an R^2 change of .130 (total adjusted R^2 for model with one factor = .128). The next predictor accepted by the model was frequency, and the change was significant, $F(1, 369) = 9.76, p < .002$, with a change in R^2 of .022 (total adjusted R^2 for model with two factors = .148). *N* was the third and final significant predictor accepted by the model, $F(1, 368) = 8.03, p < .01$, with an R^2 change of .018 (total adjusted R^2 for model with three factors = .164). The correlations among the independent variables ranged from .02 to .34. As with B.W.N., to verify that length was a significant predictor above and beyond the lexical variables, we entered each of the four lexical variables into the regression equation first and then added length as a regressor. This analysis also indicated that length was a significant predictor, $F(1, 612) = 30.57, p < .001$, with an R^2 change of .044. Once again, the finding that length was a significant predictor was expected given the pattern of R.S.B.'s results observed throughout this work, as well as the traditional description of the graphemic buffer. The addition of the two lexical factors is generally consistent with the data presented in Analyses 3a and 3b (although AoA was not a significant predictor in the regression analysis). For D.H.Y., the regression model accepted frequency and AoA as significant predictors. Frequency was the first significant predictor, $F(1, 310) = 25.71$, with an R^2 change of .077 (total adjusted R^2 for model with one factor = .074). The second variable included in the model as a significant predictor was AoA, $F(1, 309) = 34.42, p < .001$, with an R^2 change

of .093 (total adjusted R^2 for model with two factors = .164). The correlations among the independent variables ranged from .08 to .49. The lack of length as a significant predictor of word accuracy for D.H.Y. is consistent with the data we have observed thus far, as well as with the profile of an individual with impairment affecting orthographic LTM.

For V.B.R., the regression model accepted only AoA as a significant predictor. The model with AoA as a predictor was significant, $F(1, 271) = 23.92, p < .001$, with a change in R^2 of .081 (total adjusted R^2 for model with one factor = .078). The correlations among the independent variables ranged from .05 to .56. This analysis was limited by the small sample of V.B.R.'s spelling compared with that of the other individuals in the study, as well as the fact that her overall performance was quite accurate (offering less variability for the analysis). Nevertheless, the lack of length emerging as a significant predictor of word accuracy for V.B.R. is consistent with the data we have observed for her thus far, as well as with the profile of an individual with impairment affecting orthographic LTM.

In sum, the results of the multiple regression largely confirm the distinction between individuals with impairment to orthographic WM (B.W.N. and R.S.B.), for whom length is a significant predictor of spelling accuracy, and individuals with impairment to orthographic LTM (D.H.Y. and V.B.R.), for whom length does not predict spelling accuracy. With respect to the individuals with apparent impairment to orthographic WM, the multiple regression analyses indicate that B.W.N. and R.S.B. exhibit effects of lexical variables on spelling accuracy. While the results of these analyses should be interpreted with caution given the high degree of intercorrelation among some of the dependent variables, it is worth noting that these results converge with the data presented elsewhere in this paper, particularly in Analysis 3a.

GENERAL DISCUSSION

The data presented in the sections above provide strong support for the distinction between long-term memory and working memory systems in the cognitive system responsible for spelling. In particular, we presented four lines of evidence indicating two distinct profiles of spelling performance corresponding to the traditional distinction between impairment to the orthographic output lexicon and impairment to the graphemic buffer. A summary of the major patterns is presented in Table 11.

First, we found two rather distinct distributions of error types. One pattern consisted primarily of letter errors resulting mostly in nonwords, whereas the other pattern contained phonologically plausible spellings, other word errors, and morphological and semantic errors. These patterns have been, respectively, associated with impairment to the graphemic buffer (i.e., the orthographic working memory system) and the orthographic output lexicon (i.e., the long-term orthographic store). Second, we found that these different error patterns were accompanied by differential patterns of sensitivity to word length. The length of a word affected the spelling performance of the individuals with the error pattern expected from impairment affecting the graphemic buffer, even when we simultaneously control for lexical variables such as lexical frequency, AoA, N , and imageability. In contrast, the word length effect was not observed in the individuals with the error pattern consistent with impairment to the long-term memory component of the spelling system. Third, the individuals with the graphemic buffer impairment pattern exhibited the bow-shaped accuracy function across letter position, whereas the individuals with the orthographic lexicon impairment pattern did not exhibit this error distribution function. Fourth, the individuals with the orthographic lexicon impairment pattern consistently exhibited significant effects of lexical factors (frequency, AoA, etc.). The 2 individuals with the graphemic buffer pattern also exhibited effects of lexical factors on their spelling

performance, but these effects were neither as consistent nor as robust as those of the individuals with orthographic lexicon impairment. Each of these four lines of evidence supports the distinction between these two memory systems in spelling and strengthens the claim that there is an orthographic WM component (i.e., a graphemic buffer) involved in maintaining the activation of orthographic representations during the spelling process.

However, in addition to providing support for the distinction between the orthographic output lexicon and the graphemic buffer, the data also lend support to Sage and Ellis's (2004) claim that there may be lexical influences in the graphemic buffer. The evidence of possible lexical influence comes from the finding that the individuals with damage affecting the graphemic buffer displayed effects of certain lexical variables on their overall spelling accuracy. Specifically, both R.S.B. and B.W.N. showed effects of frequency and at least one other lexical variable on their overall spelling accuracy (see Analysis 3).

One interpretation of the finding of lexical effects on performance that is otherwise consistent with impairment to the graphemic buffer is that a structural distinction between the orthographic output lexicon and the graphemic buffer (i.e., LTM and WM) in the spelling systems is unfounded. While it is possible that the striking dissociations we have reported could arise from damage to a system in which the graphemic buffer refers simply to the activated portion of the orthographic output lexicon, detailed simulation work would be required to evaluate the plausibility of such a proposal. Until support for a single memory system architecture is developed, it would seem more straightforward to assume that the differences between the patterns of performance are most consistent with a system in which LTM and WM processes are structurally distinct. The "two systems" position does require, however, that we provide an account of the lexical effects observed in the spelling performance of B.W.N. and R.S.B. We take this up in the next section.

Lexical effects and the relationship between orthographic LTM and WM

We consider two possible accounts of the pattern reported above in which B.W.N. and R.S.B. exhibit mild lexical effects in their spelling performance. One possibility is *a two systems—two deficits account* according to which B.W.N. and R.S.B. each have two deficits—one affecting orthographic LTM and one affecting orthographic WM. Another is *a two interactive systems—one deficit account*, according to which there is a single deficit to orthographic working memory, and the lexical effects arise because the "activation history" of words spreads to the buffer, such that high-frequency words, which have higher activation in the orthographic output lexicon, also have higher activation in the buffer. Although we are not able to adjudicate between these two possibilities on the basis of the evidence provided here, we hope that the discussion will be useful in clarifying the alternative accounts and suggesting ways for evaluating these proposals in the future. It is worth noting that each of these accounts could account for individuals showing a relatively "pure" pattern of impairment to the graphemic buffer (i.e., no lexical effects) as appeared to be case for L.B. (Caramazza & Miceli, 1990) as well as the patterns such as those reported for B.W.N., R.S.B., and the case described by Sage and Ellis (2004) in which lexical effects co-occur with the classical symptoms of graphemic buffer impairment.

One possibility that has been considered elsewhere to account for lexical influences in performance of individuals with damage affecting the level of the graphemic buffer is that these individuals may have additional impairment affecting the lexical level, which leads to the observed effects of frequency (and other lexical variables; e.g., McCloskey et al., 1994; Tainturier & Caramazza, 1996). According to this hypothesis, individuals with deficits affecting both lexical processing and graphemic buffering would be expected to exhibit characteristic error profiles of each deficit type. However, given that B.W.N. and R.S.B. do not always exhibit the characteristics of a lexical deficit, under the two deficits hypothesis

we would postulate only mild impairment to the lexical processing system in these cases. Specifically, it is striking that, as was reported in Table 4, B.W.N. and R.S.B. each make very few errors involving phonologically plausible spellings of the target word or semantic, morphological or other word errors. In the case of impairment to the orthographic lexicon, we would expect to see errors generated by the sublexical system (phonologically plausible spellings) as well as lexical errors that differ from the target.

The two interactive systems—one deficit account posits that the mild effects of lexical variables observed in these (and other) cases of orthographic WM deficits results from the interaction between orthographic LTM and WM during production. This is consistent with findings outside the domain of spelling that indicate lexical influence and support for working memory processes. As indicated above, this interaction could take the form of feedforward cascading activation from the orthographic lexicon to the graphemic buffer and/or feedback from the graphemic buffer to the orthographic lexicon and back again.

In the case of cascading activation, as suggested by Sage and Ellis (2004) in the domain of spelling, activation is “history-preserving” in the sense that activation strength from the orthographic output lexicon spreads to its constituent graphemes in the buffer. Words that are more robustly encoded in the lexicon (e.g., high frequency, early age of acquisition words) will more strongly activate their constituent graphemes in the graphemic buffer (see Glasspool et al., 2006, for computational mechanisms). Thus, this account provides a principled explanation for observing lexical effects in individuals with impairment affecting the graphemic buffer, as in the cases reported here and in Sage and Ellis (2004).

With regard to interaction via feedback, McCloskey, Macaruso, and Rapp (2006) present evidence suggesting that there is feedback between the buffer and the lexicon. They reported on C.M., an individual whose spelling contains two related features: Letters from prior responses intrude into later responses, and there are many formal lexical errors (e.g., *dignify* → *define*). Crucially, C.M.’s other word errors contain letters from previous responses more often than predicted by chance. McCloskey et al. (2006) argued that this pattern can only be understood in a system with feedback between the level at which graphemes are represented—the graphemic buffer—and the level at which orthographic lexemes are represented—the orthographic lexicon. In order for these elements to interact, activation must flow to the buffer and then back to the lexicon prior to selection of the orthographic lexeme to be spelled. Thus, the mild lexical effects observed in R.S.B. and B.W.N.’s performance would also be expected in an interactive spreading activation framework.

In summary, we have offered two accounts of the observed lexical effects on the performance of 2 of the individuals with a pattern of impairment consistent with damage to orthographic WM. Although we cannot adjudicate between them at this time, both assume a clear distinction between orthographic LTM and WM processes and structures.

Other related patterns of acquired dysgraphia—As discussed in the introduction, Cipolotti et al. (2004) reported on an individual whose performance contained elements of deep dysgraphia and graphemic buffer impairment (also see Glasspool et al., 2006). These authors distinguish this impairment from impairment to the graphemic buffer because of the co-occurrence of semantic errors with length effects. Glasspool et al. (2006) argue that this particular pattern arises from damage to the semantic system, which has consequences downstream for the proper functioning of the graphemic buffer.

For the present purposes, it is important to note that neither of the patterns we have reported here are consistent with the functional syndrome they discuss. As indicated, the pattern includes a significant number of semantic errors in written language production (e.g., *table*

→ *chair*). However, neither B.W.N. nor R.S.B. made any semantic errors in their spelling. Further, the existence of the bow-shaped accuracy function in the performance of B.W.N. and R.S.B. is consistent with impairment to the graphemic buffer, although not observed in the case discussed by Cipolotti et al. (2004) and Glasspool et al. (2006). D.H.Y. and V.B.R. exhibit some semantic errors and a linear serial position letter accuracy function. However, one of the key elements of the functional syndrome proposed by Cipolotti and colleagues is the existence of length effects. As can be seen in Tables 3 and 5, which report the more sensitive measure of letter accuracy, neither D.H.Y. nor V.B.R. exhibits a significant effect of word length on their performance. Further, semantic errors do not require a semantic system deficit but may arise subsequent to orthographic output lexicon impairment as the semantic neighbours of a word will receive activation from the lexical semantic system and thus may be accessed in the case of an error. Thus, it is unlikely that either of the patterns reported in this paper matches the putative functional syndrome discussed by Cipolotti and colleagues (Cipolotti et al., 2004; Glasspool et al., 2006).

Also important to discuss is the fact that several individuals have been reported previously as having impairment to the graphemic buffer but not exhibiting the bow-shaped serial position accuracy function (Miceli et al., 2004; Schiller et al., 2001; Ward & Romani, 1998). As we reported above, the individuals with impairment to orthographic WM in this investigation did display this pattern with respect to spelling accuracy, even when the PGC of the target letters was controlled. We believe that the difference between the individuals reported here and those discussed in the literature are likely to be the result of disruption to different (sub)components of orthographic working memory—a complex system whose internal structure is yet to be fully understood (see Rapp & Kong, 2002).

Neuroanatomical bases for distinctions between orthographic LTM and WM

The analyses in this paper provide clear and consistent behavioural evidence supporting a distinction between orthographic LTM (the orthographic output lexicon) and orthographic WM (the graphemic buffer). With regard to the neural substrates of these components, each of the individuals we examined has a rather extensive lesion, complicating the task of drawing conclusions based on their lesions. Nonetheless, it is worth noting that the left hemisphere lesions of B.W.N. and R.S.B. are exclusively parietal, whereas V.B.R. and D.H.Y. suffer additional frontal lesions, and—at least in the case of V.B.R.—the parietal lesion is more anterior than those of B.W.N. or R.S.B. These results suggest an anterior/posterior distinction between the LTM and WM orthographic deficits. However, the broader literature regarding the neuroanatomical substrates of orthographic LTM and WM deficits does not yet present a clear and consistent picture.

Hillis and colleagues (Cloutman et al., 2009; Hillis et al., 2002) examined dysgraphic individuals in the acute phase within 24 hours of onset of left hemisphere stroke using diffusion and perfusion weighting imaging. Hillis et al. (2002; also see a case of pure dysgraphia reported in Philipose et al., 2007) found that individuals with impairment affecting the orthographic output lexicon showed hypoperfusion or infarct in BA (Broca's area) 44/45. Cloutman et al. (2009) reported that individuals with impairment affecting the graphemic buffer showed hypoperfusion or infarct across a range of left hemisphere areas including posterior and inferior frontal and parietal cortex, subcortical white matter underlying prefrontal cortex, lateral occipital gyrus, or caudate. This broad distribution of loci is also found if one considers the set of single case studies that have reported graphemic buffer deficits (for a review, see Cloutman et al., 2009).

However, in contrast to V.B.R. and D.H.Y. and the findings of Hillis and colleagues implicating BA 44/45 in lexical deficits in dysgraphia, Rapcsak and Beeson (2004), who examined the lesion distribution in a set of chronic cases of acquired lexical deficits in

dysgraphia, found the highest degree of lesion overlap to be in the left inferior temporal lobe/fusiform gyrus. Also consistent with Rapcsak and Beeson (2004), Tsapkini and Rapp (2010) presented a detailed study of a individual with a lesion restricted to the fusiform/inferior temporal area who exhibited a clear lexical deficit in spelling.

In this context, the functional neuroimaging literature might prove to be informative. Unfortunately, however, the functional neuroimaging studies of spelling that have been carried out to date with neurologically intact participants do not distinguish between the LTM and WM components of spelling and thus do not help to elucidate the lesion evidence (for a review, see Rapp & Lipka, in press). Clearly much work remains to determine the neural substrates of these mechanisms and to understand the variability in lesion location that has been reported.

CONCLUSION

The evidence reported here provides additional support, from the domain of spelling, for the classic distinction between long-term memory and working memory processes. We described four cases of individuals with acquired dysgraphia, and the analysis of their spelling performance indicated two clear and distinct patterns of performance in terms of both error types and the effect of specific factors on accuracy. These patterns map onto the traditional distinctions between impairments affecting orthographic WM impairments to lexical orthographic LTM. In particular, damage to orthographic WM was associated with clear effects of length on spelling performance, letter errors that are concentrated in the middle of words, and mild-to-moderate (if any) effects of lexical variables on spelling accuracy, as well as letter errors consisting primarily of letter substitutions, deletions, transpositions, and additions. In contrast, damage to orthographic LTM led to severe effects of lexical variables on spelling performance, no effect of length, the production of many word-based or phonologically plausible responses, and more errors at the ends of words than at the beginnings.

The clear dissociation among these cases supports the notion that WM and LTM systems are distinct—at least with respect to orthographic processing—and WM is not merely a component of LTM. In addition, we also report evidence, similar to that reported by Sage and Ellis (2004) that can be interpreted as indicating an interaction between these LTM and WM structures. These findings are consistent with findings reported by other researchers in other domains. A more precise understanding of this interaction between working and long-term memory will require further empirical and computational work.

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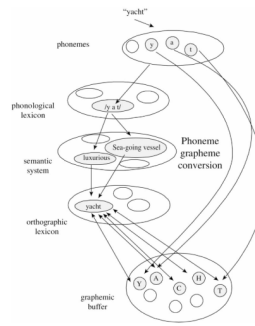


Figure 1.
Schematic representation of the cognitive processes involved in spelling to dictation.

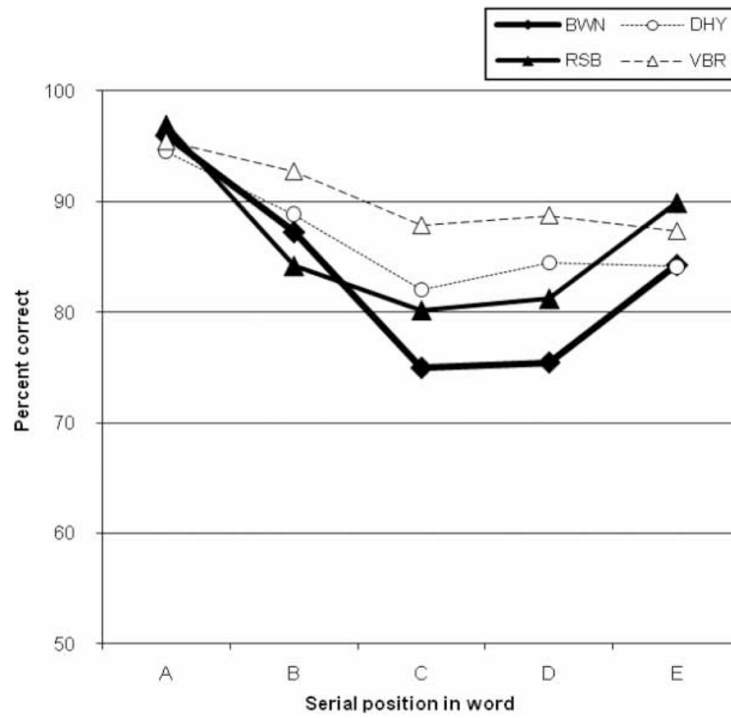


Figure 2. Spelling accuracy as a function of the serial position of letters within a word, normalized to five positions based on the scheme developed by Machtynger and Shallice (2009). All words on which the individuals were tested are used.

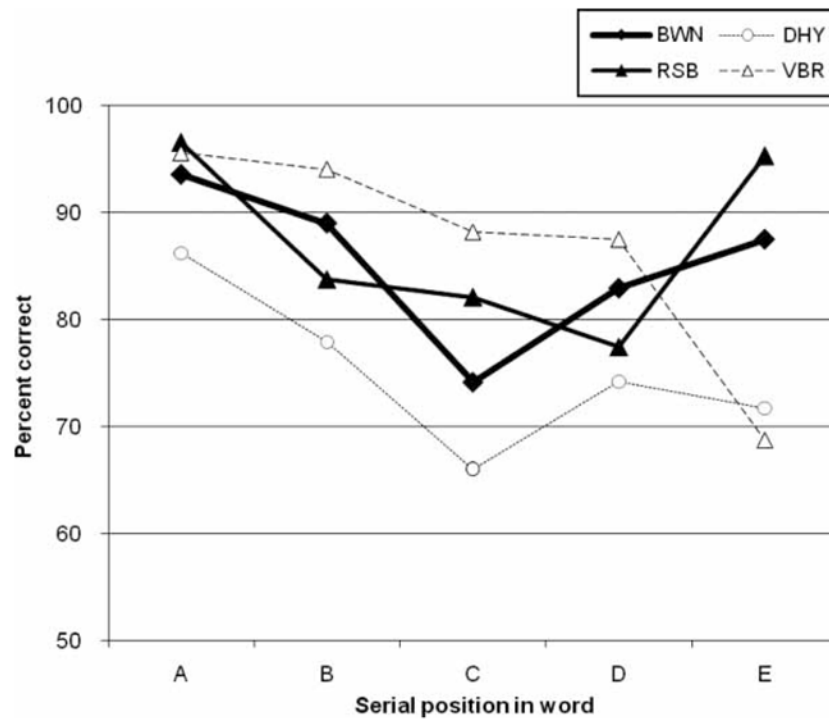


Figure 3. Spelling accuracy as a function of the serial position of letters within a word, normalized to five positions based on the scheme developed by Machtynger and Shallice (2009). This analysis consists of only those letters that have a phoneme–grapheme correspondence (PGC) probability above .80, and the mean PGC probability is matched at each serial position.

Summary of performance for each of the four individuals on a variety of language tasks, including the PPVT-R, the BORB, and a variety of tests from the PALPA

Table 1

	B.W.N.	R.S.B.	D.H.Y.	V.B.R.
Auditory discrimination: words	89 (64/72)	86 (62/72)	97 (70/72)	99 (71/72)
Auditory discrimination: nonwords	90 (65/72)	94 (68/72)	92 (66/72)	99 (71/72)
Auditory word comprehension	94th %ile	97th %ile	87th %ile	75th %ile
Auditory sentence comprehension	(15/16)	(16/16)	(14/16)	(14/16)
Spoken picture naming	68	75	—	64
	—	—	100	—
Written lexical decision	99	99	97	100

Note: Values in percentages, with number in parentheses. PPVT-R: Peabody Picture Vocabulary Test-Revised; Dunn & Dunn, 1981. BORB: Birmingham Object Recognition Battery; Riddech & Humphreys, 1993. PALPA: Psycholinguistic Assessments of Language Processing in Aphasia; Kay, Lesser, & Coltheart, 1992.

Table 2

Letter accuracy for each individual on the Length List portion of JHU Dysgraphia Battery, contrasting high-frequency and low-frequency words

	Type	%	No. correct	Analysis
B.W.N.	HF	96	404/420	$\chi^2 = 1.79, ns$
	LF	94	394/420	
R.S.B.	HF	90	377/420	$\chi^2 = 0.03, ns$
	LF	89	375/420	
D.H.Y.	HF	96	403/420	$\chi^2 = 19.68, p < .001$
	LF	87	366/420	
V.B.R.	HF	96	162/168	$\chi^2 = 13.79, p < .001$
	LF	84	142/168	

Note: JHU = Johns Hopkins University. HF = high frequency. LF = low frequency. Each individual's data in Table 2 represents two administrations of this list except for V.B.R. whose data represent one administration of all 4-, 5-, 7-, and 8-letter words on the list. **Bold** indicates a significant difference in accuracy among high- and low-frequency words ($\alpha = .05$).

Table 3

Letter accuracy for each individual on the Length List portion of JHU Dysgraphia Battery, sorted by length of target word

	Length	%	No. correct	Analysis
B.W.N.	4&5	97	245/252	$\chi^2 = 5.65, p < .01$
	7&8	92	389/420	
R.S.B.	4&5	96	241/252	$\chi^2 = 18.59, p < .01$
	7&8	84	355/420	
D.H.Y.	4&5	91	229/252	$\chi^2 = 0.22, ns$
	7&8	92	387/420	
V.B.R.	4&5	89	112/126	$\chi^2 = 0.01, ns$
	7&8	88	186/210	

Note: JHU = Johns Hopkins University. **Bold** indicates a significant difference in accuracy among short (4- and 5-letter) and long (7- and 8-letter) words ($\alpha = .05$).

Table 4

Error types for each of the individuals in this case series study

	No. of errors	Total errors	PPE	Morph	Sem	Other (word)	Other (nonword)
B.W.N.	%	—	8	0.2	0	3.5	88.0
	<i>N</i>	948	79	2	0	33	834
R.S.B.	%	—	6.7	0	0	6.0	87.3
	<i>N</i>	1,010	68	0	0	61	881
D.H.Y.	%	—	21.5	12.3	3.8	21.5	40.8
	<i>N</i>	130	28	16	5	28	53
V.B.R.	%	—	20.8	17.9	4.5	25.3	31.3
	<i>N</i>	67	14	12	3	17	21

Note: PPE refers to phonologically plausible errors, Morph refers to morphologically related errors, and Sem refers to semantically related errors. All errors are included.

Table 5

Word accuracy and letter accuracy for each individual on revised Lavidor and Ellis (2002) list controlling for frequency, imageability, age of acquisition, and N

	Length	Letters		Words	
		%	Analysis	%	Analysis
B.W.N.	5	93	$\chi^2 = 13.22, p < .001$	71	$\chi^2 = 10.93, p < .001$
	8	81		31	
R.S.B.	5	91	$\chi^2 = 8.72, p < .01$	55	$\chi^2 = 19.91, p < .001$
	8	80		18	
D.H.Y.	5	82	$\chi^2 = 0.01, ns$	66	$\chi^2 = 5.73, p < .05$
	8	81		36	
V.B.R.	5	89	$\chi^2 = 1.88, ns$	71	$\chi^2 = 4.85, p < .05$
	8	84		44	

Note: There were 38 five-letter words (190 letters) and 39 eight-letter words (312 letters). **Bold** indicates a significant difference in accuracy between five- and eight-letter words ($\alpha = .05$).

Table 6

Word accuracy and letter accuracy for each individual on original Lavidor and Ellis (2002) list controlling for frequency, imageability, age of acquisition, and N, for which morphological complexity was not controlled

	Length	Letters		Words	
		%	Analysis	%	Analysis
B.W.N.	5	92	$\chi^2 = 5.15, p < .05$	66	$\chi^2 = 2.49, ns$
	8	84		47	
R.S.B.	5	86	$\chi^2 = 0.43, ns$	54	$\chi^2 = 2.05, ns$
	8	84		36	
D.H.Y.	5	79	$\chi^2 = 1.19, ns$	59	$\chi^2 = 2.82, ns$
	8	75		38	
V.B.R.	5	90	$\chi^2 = 0.29, ns$	73	$\chi^2 = 0.84, ns$
	8	88		62	

Note: There were 41 five-letter words (205 letters) and 47 eight-letter words (376 letters). **Bold** indicates a significant difference in accuracy among five- and eight-letter words ($\alpha = .05$).

Table 7

Overall spelling performance for each individual, broken into short/long, high/low frequency, N, imageability, and AoA

	B.W.N.	R.S.B.	D.H.Y.	V.B.R.
Short	95	89	84	94
Long	90	80	83	93
High frequency	95	89	90	96
Low frequency	90	82	73	90
High <i>N</i>	93	89	86	95
Low <i>N</i>	92	85	83	91
High imageability	93	87	96	97
Low imageability	94	88	85	92
Early acquired	96	89	93	97
Late acquired	92	85	70	89
	<i>n</i> = 1,707	<i>n</i> = 2,144	<i>N</i> = 598	<i>N</i> = 629

Note: AoA = age of acquisition. Spelling performance: letter accuracy, in percentages. See text for details. **Bold** reflects significant differences in spelling accuracy as evaluated by chi-square ($\alpha = .05$).

Table 8

Performance on Morrison and Ellis (1995) list contrasting high-frequency and low-frequency words in groups matched for age of acquisition

Type	Early acquired			Late acquired		
	%	No. correct	Analysis	%	No. correct	Analysis
B.W.N. HF	94	59/63	<i>ns</i>	81	73/90	$\chi^2 = 0.02, ns$
LF	87	55/63		81	70/86	
R.S.B. HF	100	63/63	<i>ns</i>	89	80/90	$\chi^2 = 0.97, ns$
LF	94	59/63		83	71/86	
D.H.Y. HF	100	63/63	<i>p</i> < .001	97	87/90	<i>p</i> < .001
LF	82	49/60		63	54/86	
V.B.R. HF	100	63/63	<i>p</i> < .05	98	85/87	<i>p</i> < .001
LF	57	57/63		75	65/86	

Note: HF = high frequency. LF = low frequency. Results presented are letters correct; for early acquired words. Significant differences are denoted in **bold**. Statistical tests were chi-square, except for comparisons with cell values smaller than 5, which were computed with Fisher's Exact.

Table 9

Performance on AoA portion of Gerhard and Barry (1998) word list contrasting early-acquired words with late-acquired words

	Type	%	No. correct	Analysis
B.W.N.	EA	90	112/125	$\chi^2 = 0.85, ns$
	LA	85	107/126	
R.S.B.	EA	91	114/125	$\chi^2 = 0.96, ns$
	LA	87	109/126	
D.H.Y.	EA	96	121/125	$p < .0001$
	LA	74	93/126	
V.B.R.	EA	99	124/125	ns
	LA	98	124/126	

Note: AoA = age of acquisition. EA = early acquired. LA = late acquired. Results presented are letters correct. Significant differences ($\alpha = .05$) are denoted in bold. Statistical tests were chi-square, except for comparisons with cell values smaller than 5, which were computed with Fisher's Exact.

Table 10

Performance on frequency portion of Gerhard and Barry (1998) word list, contrasting high-frequency and low-frequency words

	<i>Type</i>	<i>%</i>	<i>Correct</i>	<i>Analysis</i>
B.W.N.	HF	93	107/115	$\chi^2 = 0.87, ns$
	LF	89	101/114	
R.S.B.	HF	98	113/115	$p < .01$
	LF	89	101/114	
D.H.Y.	HF	94	108/115	$\chi^2 = 11.65, p < .01$
	LF	77	88/114	
V.B.R.	HF	100	115/115	$p < .01$
	LF	93	106/114	

Note: HF = high frequency. LF = low frequency. Results presented are letters correct. Significant differences are denoted in bold. Statistical tests were chi-square, except for comparisons with cell values smaller than 5, which were computed with Fisher's Exact.

Table 11

Summary table of performance for each individual

	B.W.N.	R.S.B.	D.H.Y.	V.B.R.
Letter errors	Common	Common	Rare	Rare
PPEs and word errors	Rare	Rare	Common	Common
Length effect	Consistent	Consistent	Absent	Absent
Serial position effect	Bow-shaped	Bow-shaped	Linear	Linear
Lexical effects	Mild	Mild	Severe	Severe

Note: PPE = phonologically plausible error. The first two rows are based on the analyses in the section “Localizing the Deficits”. The third row is based on Analysis 1, the fourth row is based on Analysis 2, and the fifth row is based on Analysis 3.