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# Complex Graphemes as Functional Spelling Units: Evidence from Acquired Dysgraphia

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#### Abstract

The visual word recognition literature suggests that complex graphemes (or digraphs) such as CK function as units. This proposal has also been put forward in recent spelling models (Houghton and Zorzi, 2003) and the study we report on here provides initial empirical support for the claim. We performed detailed analyses of the spelling performance of two brain-damaged individuals with graphemic buffer deficits. Results revealed that (a) FM and BWN made fewer errors on consonant digraphs (e.g., CK) than on matched controls clusters (e.g., CR) and (b) BWN produced more transposition errors on vowel digraphs than on control clusters. These results support the view that digraphs are represented as units in which the relative order of constituent letters is encoded.

According to most current theories, spelling involves at least two sets of processes (Fig. 1). First, a spelling can be generated sublexically by relying on knowledge of the frequent correspondences between phonemes and graphemes. This sublexical phonology to orthography conversion process generates plausible spellings for both familiar and unfamiliar words (or pseudowords). However, the output may not be entirely accurate in orthographically opaque languages such as English because many words have an ambiguous or irregular spelling (e.g., the word ''phone'' could be spelled ''fone''). Second, the spelling of familiar words can be generated lexically, by accessing a stored representation of the spelling of words in an orthographic lexicon. This would allow familiar words to be spelled correctly. Although it can be assumed that the spelling of nonwords is mostly generated sublexically while that of familiar words is mostly generated lexically, lexical and sublexical processes will jointly contribute to the activation of a set of abstract graphemic units (see Fig. 1 and Rapp et al., 2002; Bosse et al., 2003). It has been proposed (Caramazza et al., 1987) that the abstract orthographic representations generated by these processes will be held by a dedicated short-term memory process (graphemic buffer) during the operation of more peripheral mechanisms responsible for transforming abstract orthographic representations into form representations that are specific to the chosen modality and format of output (e.g.,

print, cursive, oral spelling, typing, upper/lower case and so on). This buffering process is required due to the sequential nature of letter name/shape selection processes.

But what is the content and organization of the orthographic representations that are held at the grapheme level? What information is represented? How is it structured? Minimally, orthographic representations must encode information about letter identity and order (e.g.,  $C_1A_2T_3$ ). However, several lines of evidence now support the idea that orthographic representations are more than linear sequences of abstract letter identities (for a review, see Tainturier and Rapp, 2001). Most of this evidence comes from the analysis of the error patterns of dysgraphic individuals, although there is some converging evidence from studies of normal spellers. Studies of ''graphemic buffer deficits'' have proved particularly revealing. Such deficits typically lead to letter substitutions, omissions, additions and transpositions that are taken to reflect the disruption of information about letter identity and order that occurs when the graphemic buffering capacity has been compromised. If orthographic output representations were merely linear sequences of letter identities, one would not expect the nature and position of letter errors to be affected by factors that assume a more complex, non-linear organization of the letter identities. Yet, several results indicate that orthographic representations are, in fact, internally complex.

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Fig. 1. The spelling process.

First, there is evidence that morphemic structure is encoded in orthographic representations (for a review, see Allen and Badecker, 2001). A clear demonstration was provided in a study of case DH (Badecker et al., 1990). In addition to the characteristic features of a graphemic buffer deficit, DH's spelling showed a serial position effect such that the probability of an error on a given letter increased as a function of the position of that letter in the word. Strikingly, however, this pattern only held for monomorphemic words like ''car''. In the case of bimorphemic words like ''darkness'', error rates increased up to the end of the word stem (''dark'') but then dropped on the first letter of the suffix to increase again on subsequent letters. This indicates that the information retrieved from the orthographic lexicon and later held in the graphemic buffer is organized into morpheme-sized units rather than whole words.

Second, Caramazza and Miceli (1990; see also Ward and Romani, 2000) have proposed that orthographic representations also encode information about syllabic structure (but see Jónsdóttir et al., 1996). This conclusion was partly based on the observation that case LB, an Italian patient with a graphemic buffer deficit, showed a marked tendency to simplify the syllabic structure of words. For example, letter omissions were frequent in the context of letter clusters, usually leading to simpler syllabic structures (e.g., "creatura"  $\rightarrow$  RETURA). However, omissions virtually never occurred in simple CV sequences, where an omission would create a more complex syllable (that is, LB did not produce errors such as "creatura"  $\rightarrow$  CREATRA). In a typing study with normal participants, Zesiger et al. (1994) also demonstrated an influence of syllabic structure on the temporal course of spelling: the interval between two strokes was shorter if the two corresponding letters belonged to the same syllable than if they did not.

Third, several studies of graphemic buffer deficits have shown that information about specific letter identities can be lost while knowledge of the consonant/vowel status of these letters is preserved. In several cases (Miceli et al., 1985; Caramazza and Miceli, 1990; McCloskey et al., 1994; Jónsdóttir et al., 1996; Buchwald and Rapp, 2003) substitution errors virtually always occurred within class, with consonants being substituted for consonants and vowels for vowels. This suggests that letter identity and consonant/vowel status may be represented separately. In addition, there have been several reports of patients who made many more errors on vowels than on consonants (Cubelli, 1991; Cotelli et al., 2003) and vice versa (Miceli et al., this issue).

Finally, there is strong empirical support for distinct and dissociable representations of letter identity and of letter doubling information (Caramazza and Miceli, 1990; McCloskey et al., 1994; Miceli et al., 1995; Tainturier and Caramazza, 1996). For example, Italian case SFI (Miceli et al., 1995) had a selective deficit in the production of double letters leading to errors like leggo  $\rightarrow$  LEGO. Case FM (Tainturier and Caramazza, 1996) showed the reverse pattern, with doubling information being much better preserved than letter identity. Consistent with the view that information about letter doubling and letter identity is dissociable, FM often replaced a double-letter with another double-letter (e.g., umbrella  $\rightarrow$ UMMOUCAN, ribbon  $\rightarrow$  BROLLOW). Furthermore, the study showed that the representation of double-letters is distinct from that of other superficially similar groups of letters such as non-adjacent repeated letters (e.g., CaCtus) or digraphs (e.g., roCKet).

In summary, there is considerable evidence that orthographic representations are more than simple linear sequences of abstract letter identities. In particular, various factors such as morphological and syllabic structure, letter doubling and CV status can affect the patterns of errors of dysgraphic subjects or the temporal properties of normal spelling. In this article, we will examine whether letter sequences that correspond to a single phoneme (such as  $/k / \rightarrow CK$  in ROCKET or  $/f\rightarrow$  PH in PHONE) are represented and processed differently from otherwise similar letter sequences that do not correspond to a single phoneme (such as ST or PL). We will refer to sequences such as CK and PH as complex graphemes or digraphs.

In their connectionist simulation of the spelling process, Houghton and Zorzi (2003) have proposed that letter sequences that correspond to a single phoneme are represented as single units, even when they include more than one letter. Thus, in terms of abstract grapheme representations, a word such as ''wreath'' is composed of three grapheme units  $(WR + EA + TH)$ , while "strict" is composed of six  $(S + T + R + I + C + T)$ . Both do, of course, include six letters, which becomes relevant at subsequent stages of production (see Fig. 1). The proposal that complex graphemes differ from other sequences such as CR or ST is intuitively appealing because, for sequences such as  $/f / \rightarrow PH$ , the correspondence between orthography and phonology is much more transparent at the level of graphemes than at the level of single letters. Furthermore, this proposal is supported by the finding of Houghton and Zorzi (2003) that treating complex graphemes as units improved both the accuracy and plausibility of responses of their spelling simulation.

In the written word recognition and reading literature, there is some empirical support for the view that complex graphemes (other than double letters) are processed as units. Rey et al. (2000) have shown that it takes longer to detect a single target letter when it forms part of a complex grapheme than when it does not (e.g., detecting the letter O in the written word FLOAT as opposed to SLOPE). Their interpretation of this finding is that multi-letter graphemes function as perceptual units in reading, making it harder to detect letters that are embedded within them. Consistent with the view that digraphs are processed as units, Pring (1981) reported that case-alternated words were recognised more slowly when case alternation disrupted the unity of digraphs (e.g., BREad) than when it did not (BRead). Similar results were obtained by Martensen *et al.* (2003) using slashes to visually separate letters: words such as 'bre//ad' were recognised and named more slowly than words such as 'br//ead'. Dickerson (1999), Joubert and Lecours (2000) and Rastle and Coltheart (1998) provide further evidence for a distinct processing of complex graphemes in reading. In addition, Plaut et al. (1996) were able to significantly improve upon the performance of the connectionist reading simulation reported by Seidenberg and McClelland (1989) by representing the input to the reading system in terms of graphemes.

If complex graphemes are represented at the abstract grapheme level, what might we observe subsequent to neurological injury affecting the spelling process? Our expectation would be that a process that is sensitive to the number of elements in a representation (e.g., graphemic buffering) should show an advantage for complex graphemes over sequences of simple graphemes. This is because there would be less information to activate and buffer for a word such as WREATH (three graphemic units) than for a word such as STRICT (six units).

On the other hand, complex graphemes may be at a disadvantage later in the spelling process, given that spelling ultimately involves the serial production of individual letters. If complex graphemes have a unitary representation at one level of processing there must be a later stage of processing at which their constituent components must be identified or recovered. In order for this to be accomplished, we must assume that a digraph's constituent letters and their ordering are represented in a manner (e.g.,  $[W_1 R_2]$ ) which subsequent processes can interpret or ''unpack'' (Fig. 1). Consequently, although complex digraphs may have an advantage over clusters at one level, they may be more complex than cluster sequences at the stage that requires the identification and ordering of their constituent elements. Relevant to this discussion is the proposal that there is a distinction between the activation and maintenance of orthographic information on the one hand, and the serially ordered selection of the buffered letters for production on the other (Houghton et al., 1994; Rapp and Kong, 2002; Houghton and Zorzi, 2003). Although digraphs have not been specifically discussed (or modeled) in terms of the proposed activation/selection processes, it would seem that the process responsible for selecting letters for production must not only preserve the order of the elements that have been activated and buffered but that it would also need to recover the order of letters within digraphs. Given the proposed internal structure of digraphs, if the selection/ unpacking process is disrupted, we might expect digraphs to be particularly vulnerable to transpositions of their constituent elements (e.g., "wreath"  $\rightarrow$  WRAETH). Blanken *et al.* (1999) present evidence which is generally consistent with this view. Also consistent with the view that digraphs might be more vulnerable at some level of the spelling process, Caramazza and Miceli (1990) reported that Italian patient LB tended to write the sequence ''sc'' less accurately when it corresponded to a single phoneme as in ''scena'' /sena/ (29.2% errors) than when it corresponded to two phonemes as in ''scusa'' /skuza/ (17.9% errors). However, these particular findings should be taken with caution, as digraphs and control clusters were not matched on a number of variables which strongly affect the performance of individuals with graphemic buffer deficits, such as word length and position of the sequence within the word.

In this study, we will provide empirical support for the view that complex graphemes (such as those in  $WR + EA +$ TH) are represented in a unitary manner at some level of the spelling system, as proposed in Houghton and Zorzi (2003). This will be done through a detailed analysis of the spelling errors of two individuals with acquired graphemic buffer deficits: FM and BWN. We will also present evidence of the internal organization of digraphs based on an analysis of the transposition errors produced by case BWN.

## Methods and results

This section will be organized as follows: we first present case histories of the two individuals who are the subjects of this report, FM and BWN; we then present evidence that they suffer from deficits affecting the buffering of abstract graphemes; finally, we present experimental findings regarding their spelling of digraphs and control segments.

#### Case histories

#### FM

At the time the data for this study were collected, FM was a 46 year-old male who had suffered a stroke ten years earlier. He was right-handed and a high school graduate who had been working as a truck driver prior to the stroke. A CT-scan performed two years post-stroke revealed a large area of damage in the territory of the left middle cerebral artery. More specifically, damage involved the infero-posterior frontal lobe, the inferior parietal lobe and the anterior temporal lobe, as well as the underlying white matter and lateral basal ganglia; there was also cortical atrophy of the remainder of the left frontal convexity.

At the time FM's spelling was investigated, FM showed right hemianopia, hemiparesis mostly affecting the upper limb, and he was still severely aphasic. His language disorder would be clinically characterized as agrammatic Broca's aphasia. That is, his speech was laborious and 'telegraphic', with word finding difficulties, phonetic/phonological errors and morphological errors. Spoken comprehension was very well preserved, except for syntactically complex sentences (see Badecker et al., 1991). FM's reading aloud was also severely impaired and characteristic of deep dyslexia. Specifically, he was most impaired for long, abstract and low-frequency words, and his performance was affected by grammatical category, such than nouns were read better than adjectives, which were read better than verbs, which were read better than function words. FM could not read aloud pseudowords and, when reading words, he produced visual, semantic, visual/semantic and morphological errors. More details on FM's reading impairment can be found in Badecker and Caramazza (1987).

#### BWN

BWN was a 79 year-old, right-handed man who had suffered two strokes, four years and one year prior to the onset of this investigation. He held a Ph.D., had worked as a teacher, a high-level school system administrator and was president of the city chapter of a prestigious civic organization. Premorbidly, BWN was an excellent public speaker and speller. While in school he had been a finalist in regional spelling competitions and his editorials and letters to local newspapers reveal a man who was particularly gifted in written expression. CT scans indicate an older left parietal lesion and a more recent right parietal lesion (see Fig. 2). The left hemisphere lesion is the larger of the two, extending in the superiorinferior dimension from the superior parietal gyrus to the superior temporal gyrus and, in the anterior-posterior dimension, from the post-central gyrus to the angular gyrus. The right hemisphere lesion affects the posterior parietal lobe, including the angular and superior parietal gyri.

As a result of his strokes, BWN suffered mild right-sided weakness and some somatosensory loss in the right hand but he showed no evidence of visuo-spatial neglect. He had moderate difficulties in spoken language production, primarily characterized by word finding difficulties and phonological errors. Although BWN suffered mild hearing loss and had some auditory discrimination difficulties (word discrimination 90%, nonword discrimination 91%, mean normal performance 98%), his auditory word and sentence comprehension was very good. Written comprehension was also good (e.g., 100% correct in synonym matching for abstract and concrete words) and he read the newspaper for pleasure, although not as easily as he had prior to the strokes. His spelling difficulties are described below.

#### Graphemic buffer deficits

Characteristics of a selective graphemic buffer deficit (Caramazza et al., 1987) include: (a) a significant effect of



Fig. 2. BWN's CT scan.

word length (measured in letters rather than phonemes); (b) errors consisting of letter substitutions, deletions, transpositions and additions (and not phonologically plausible errors or semantic errors); (c) comparable performance across modality of input (e.g., in spelling to dictation, written picture naming, delayed copy transcoding); (d) comparable performance across modality of output (oral or written spelling); (e) comparable performance across stimulus types (words/nonwords, regular/irregular, abstract/concrete); (f) absence of an effect of lexical frequency; (g) a bow-shaped accuracy function across letter positions such that performance is most accurate with initial and final letters and least accurate with letters in the center of words.

#### FM

FM's spelling performance has been presented in detail elsewhere (Tainturier and Caramazza, 1996) and will only be summarised here. FM's spelling was tested extensively 10 years after his stroke. Over a period of approximately 15 months, a large corpus of errors was collected in spelling to dictation (823 stimuli), written picture naming (379 stimuli), and delayed copy transcoding (842 stimuli). In the latter task, FM was asked to reproduce in uppercase a stimulus that had been presented in

lowercase and then hidden from view. This task is assumed to require graphemic buffering to maintain the activation of letter identities while the forms of the letters are produced.

Performance in these three tasks showed the characteristics of a graphemic buffer deficit. First, the deficit affected all stimulus types (regular words, irregular words and nonwords) and was very similar across the three spelling tasks which, despite differing in input, all make use of the graphemic buffer. Second, errors increased markedly with stimulus length (see Fig. 3). Third, there was a serial position effect that has been reported for a number of graphemic buffer deficits, such that letters from medial positions were less likely to be produced correctly than letters in initial and final positions. Finally, the type of errors reflected a disruption of information about letter identity and order. Thus, the majority of errors were nonword responses that differed in their degree of similarity to the targets (pea  $\rightarrow$  PAE; grapes  $\rightarrow$  GPAGE). More specifically, most errors could be described in terms of single letter substitutions (panel  $\rightarrow$  PADEL), deletions (apri- $\cot \rightarrow APICOT$ ), misorderings (ground  $\rightarrow$  GRONUD), additions (beauty  $\rightarrow$  BEAUNTY), or various combinations of the above. As can be seen in Fig. 4, the distribution of single-letter



Fig. 3. Case FM: The effect of word length in spelling to dictation (STD), written picture naming (WPN) and delayed copy transcoding (DCT).



Fig. 4. Case FM: The distribution of single-letter errors in three spelling tasks.

errors was very similar across all three tasks. This set of characteristics is clearly indicative of a deficit at the level of the graphemic buffer.

FM's performance in spelling to dictation and written picture naming also suggested an additional deficit to the lexical semantic system and/or the orthographic output lexicon, given that FM produced semantic errors in those tasks (11% and 16%, respectively). In delayed copy transcoding, which involves the graphemic buffer but does not require lexical mediation, FM produced fewer semantic errors (2%), his errors tended to be closer to the targets, and overall accuracy was higher (54% errors in delayed copy transcoding, versus 76% in spelling to dictation and 66% in written picture naming). This is consistent with the view that performance in delayed copy transcoding reflected almost exclusively the graphemic buffer deficit, while performance in the other two tasks was influenced by the additional lexical deficit.

#### BWN

BWN's spelling performance clearly indicated that his spelling errors arose at the level of the graphemic buffer (see also Buchwald and Rapp, 2003). BWN was administered 3947 words (between 4 and 10 letters in length) for written spelling. Because of his mild hearing loss, BWN was asked to either repeat each stimulus or indicate its meaning prior to spelling the word. If a stimulus was misperceived, it was repeated until BWN demonstrated that he had correctly understood it and only then did he spell it. BWN spelled 24% of words incorrectly and (see Table 1) his error rate for long words (8–10 letters) was significantly greater than his error rate for short words (4–6 letters), whether accuracy is calculated in terms of word errors ( $\chi^2$  = 539.2, p < .0001) or letter errors  $(\chi^2 = 594.8, p < .0001)$ . Furthermore, as indicated in Fig. 5, BWN exhibited the characteristic bow-shaped accuracy function across letter positions ( $n = 30$  at each length), regardless of word length.

BWN's spelling errors were almost entirely letter errors: substitutions (22.5%; 213/948); deletions (39.3%; 373/948) additions (3.9%; 37/948); and exchanges (10.2%; 97/948). The remaining errors (24.1%; 228/948) were some combination of these single-letter errors (e.g., 'claw'  $\rightarrow$  CRACW). Only 79 (8.3%) of the 948 word errors were phonologically

Table 1. BWN's spelling performance according to word length (length measured in letters)

Length	Word errors	$\%$	Letter errors	$\%$
4	16/382	4.2	16/1528	1.0
5	125/926	13.5	146.5/4630	3.2
6	121/879	13.8	166/5274	3.1
7	217/844	25.7	298/5908	5.0
8	239/486	49.2	376/3888	9.7
9	158/293	53.9	356/2637	13.5
10	72/137	52.6	189/1370	13.8
Totals	948/3947	24.0	1547.5/25235	6.1



Fig. 5. Case BWN: Percentage of letters correctly produced as a function of letter position and word length.

plausible spellings of the target word, with 76 of the 79 (96.2%) consisting of single letter substitutions (e.g., 'facet'  $\rightarrow$  FACIT), deletions (e.g., 'chrome'  $\rightarrow$  CROME), insertions (e.g., 'mistress'  $\rightarrow$  MISSTRESS), or transpositions (e.g., 'deuce'  $\rightarrow$  DUECE). The three remaining phonologically plausible errors involved some combination of single letter errors. Thus, although the phoneme/grapheme conversion system cannot be ruled out as the source of some of these responses, they are all consistent with a graphemic buffer deficit. In addition, BWN did not produce semantic errors in spelling to dictation.

BWN's performance across modalities of input was evaluated with spelling to dictation and delayed copy transcoding on the same stimulus set of sixty 7–10 letter words. As indicated in Table 2, his level of performance was very similar across the two tasks (word accuracy:  $\chi^2(1) = 0.106$ , ns; letter accuracy:  $\chi^2(1) = 0.006$ , ns) and there were comparable length effects. Furthermore, BWN's performance was virtually identical across output modalities when oral and written spelling were evaluated with the same set of seventy 4–8 letter words, yielding word error rates of 23% (oral spelling) and 21% (written spelling;  $\chi^2$  = 0.00, ns) and letter error rates of 5% in both modalities.

Table 2. Case BWN: Spelling performance as a function of word length and input modality (spoken versus visual)

Length	Spelling to dictation		Delayed copy transcoding	
	Word errors	Letter errors	Word errors	Letter errors
7	$40\%$ (6/15)	9% (10/105)	53% (8/15)	11% (12/105)
8 9	60% (9/15) 73% (11/15)	16% (20/120) 21% (29/135)	$60\%$ (9/15) 80% (12/15)	17% (20/120) 27% (36/135)
10	93% (14/15)	33% (50/150)	93% (14/15)	26% (39/150)
Totals	67\% (40/60)	21% (109/510)	72% (43/60)	21% (107/510)

Further evidence that BWN's spelling errors did not arise from damage to the lexical process comes from the apparent lack of an effect of frequency on his spelling performance. BWN was administered a list of 60 words of high (mean  $= 55$ ) and low-frequency (mean  $= 5.3$ ) (Francis and Kucera, 1982), matched for length. There was no significant difference in his spelling performance on these lists either in terms of word accuracy  $(\chi^2(1) = 1.0$ , ns) or letter accuracy  $(\chi^2(1) = 2.9)$ ,  $p < .09$ ). BWN was also administered three lists of words contrasting the extremes of the frequency continuum (high frequency  $> 100$ ; low frequency  $< 10$ ) (Francis and Kucera, 1982). On two of these three lists, there was no significant difference in his performance with high- and low-frequency words. These results, in combination with the relatively small number of phonologically plausible errors, the absence of semantic errors, no significant effects of concreteness/ abstractness ( $\chi^2$  = 0.0) or of regularity ( $\chi^2$  = 1.53, p < .22), all indicate that BWN is unlikely to suffer from an additional lexical impairment.

The only area that we were unable to adequately assess was BWN's spelling of nonwords. This assessment was complicated by the combination of his mild hearing loss and phonological errors in spoken production. Consequently, if he repeated a nonword stimulus incorrectly we couldn't be certain if he had misperceived it and then correctly repeated his misperception or if, instead, he correctly perceived the stimulus but incorrectly repeated it, or both. Note that the situation was different for words as with these BWN was able to communicate the meaning of any word he repeated incorrectly, allowing us to be confident of his perception. As a result, BWN was not tested extensively with nonwords. Out of 56 nonwords, he spelled 21 correctly (37.5%), with a letter accuracy rate of 82.1%. Accuracy was poorer with nonwords as compared to words, although error types were the same, consisting of letter substitutions ("scart" $\rightarrow$  SCARK), deletions ("cantree"  $\rightarrow$  CATRE), insertions ("foit"  $\rightarrow$  FOINT) and misorderings ("remun"  $\rightarrow$  RUMEN). Given the difficulties in evaluating nonword spelling, we cannot be certain if the accuracy difference between words and nonwords is due to errors in perception or an additional deficit affecting phonology-orthography conversion. However, even if the latter were to be the case, it would not have any bearing on the interpretation of the experimental work we present below.

In sum, BWN's performance is precisely that expected from a graphemic buffer deficit which compromises an individual's ability to maintain the activation of orthographic representations.

# Experiment 1: Analysing the relative preservation of digraphs and control clusters

In earlier analyses of FM's spelling deficit (Tainturier and Caramazza, 1996), there was some indication that digraphs such as SH behaved differently from control clusters such as ST. More specifically, FM was less likely to produce only one of the two target letters in digraphs than in control sequences (22/68 vs. 32/68 in spelling to dictation, 7/20 vs. 10/20 in written picture naming, and 15/78 vs. 23/78 in delayed copy transcoding; non-significant differences). That is, FM produced fewer errors such as "rocket"  $\rightarrow$  ROCET or ROCLET than errors such as "basket"  $\rightarrow$  BASET or BASPET. However, this aspect of FM's performance was not pursued further at the time since the main goal of the earlier study was to demonstrate that double-letter sequences (as in RABBIT) were processed differently from other types of letter sequences, including digraphs, something which was clearly shown to be the case.

In this experiment, we further investigated FM's processing of digraphs using a larger and better controlled set of stimuli presented in a delayed copy transcoding task. For BWN we examined his performance in spelling to dictation a list of consonant digraphs and matched controls that was developed specifically for assessing digraph spelling.

#### **Methods**

For FM we undertook a post hoc analysis of a large corpus of spellings obtained in a delayed copy transcoding task. In this task, the experimenter showed words typed in lowercase characters, the stimulus was then covered and FM was asked to write it using uppercase letters. As we have seen, performance in delayed copy transcoding was very similar to that in other spelling tasks. We chose to analyse data from this task, as opposed to spelling to dictation, because it provided a sufficient number of items suitable for the digraph analysis and because performance in this task was not confounded by FM's lexical deficits (as explained above), and therefore, is a more direct reflection of the graphemic buffer deficit.

From the existing corpus of 842 stimuli, we selected 5 to 9 letter words that included a consonant digraph (e.g., sh, ck) and matched them to words from the corpus that included consonant clusters (e.g., st, cr) but no digraphs. Only consonant digraphs were included as there were very few possible controls for vowel digraphs in the corpus (i.e., there were very few words such as ''lion'' in which the vowel sequence does not correspond to a single phoneme). Words with digraphs and clusters were matched pairwise for (a) word length in letters, (b) the position of the target sequence in the word (word initial, word final, and medial positions), and (c) the consonant/vowel context of the target sequence (whether the target sequence is preceded or followed by a vowel or a consonant). Digraph and control sequences were also matched listwise for bigram frequency (Mayzner and Tresselt, 1965). This was to ensure that any potential advantage of digraphs over control sequences could not be attributed to the frequency with which the two component letters co-occur in English. The application of these criteria yielded an experimental list of 232 words (116 matched pairs). Examples include: SHOWER-PLANET, OSTRICH-HARVEST, MORPHINE-COMPLETE (target sequences underlined). Note that word pairs were not matched for lexical frequency because there was no evidence that this factor affected FM's performance in the delayed copy transcoding task. For example, in this task FM correctly produced 31/80 six-letter words with frequencies ranging from  $0-20$  (Mean = 7) and 30/80 six-letter words with frequencies ranging from 21–442  $(Mean = 105)$ .

For BWN we developed a list of 30 pairs of 7–10 letter words matched pairwise for length and frequency with the consonant digraphs and control clusters in the central (more error-prone) positions (e.g., PURCHASE/CONTRACT). For this stimulus set, the digraphs and clusters were not matched for bigram frequency, digraphs having a higher bigram frequency than the clusters (1330 vs. 427;  $t = 2.98$ ,  $p < .006$ ; Mayzner and Tresselt, 1965). We address this point in the General Discussion. BWN was administered this 60 stimulus list twice for spelling to dictation; the results of each administration were extremely similar and, therefore, the data from the two administrations were combined. All chi-square analyses use a Yates correction for continuity.

#### Results

Regardless of the accuracy of non-target letters in the stimuli, responses to each of the target sequences were scored as belonging to one of three categories. The first category (sequence present) includes responses in which the target sequence (digraph or control cluster) was preserved, i.e., both target letters were produced, adjacent to one another and in the correct relative order. In the second category (sequence absent), neither of the two target letters appeared anywhere in the response. The third category (sequence ''broken'') includes cases in which (a) one and only one of the two letters was produced or (b) the two letters were produced but in non-adjacent positions. Examples of each type of errors are presented in Table 3. If complex graphemes such as ''CK'' (digraphs) function as units, one would expect that there should be fewer cases of 'broken' sequences for these sequences as compared to control letter clusters such as''ST''.

This is precisely what the analysis revealed. The distribution of each category of response for each type of target sequence is presented in Fig. 6. For both FM and BWN, there were fewer cases of''broken''sequences in the case of digraphs than in the case of control clusters (FM:  $\chi^2(1) = 7.09$ , p < .01; BWN:  $\chi^2(1) = 5.7$ , p < .02). In addition, and also consistent with the hypothesis that they are processed as units, digraph sequences were more often produced correctly than control sequences (FM:  $\chi^2(1) = 6.23$ , p < .01; BWN:  $\chi^2 = 4.58$ , p < .04).

Table 3. Case FM: Examples of the three error types analysed in Experiment 1 (target letters in boldface)

	Digraph targets	Control targets
Sequence present	knife $\rightarrow$ KNIFE $radish \rightarrow RISDISH$	$\text{crime} \rightarrow \text{CRIME}$ blister $\rightarrow$ BISTEN
Sequence absent	$ostrich \rightarrow OSTRIP$ machine $\rightarrow$ MAEMISE	anglican $\rightarrow$ ACNINT hermit $\rightarrow$ HINDOE
Sequence broken	$p$ ocket $\rightarrow$ POCTER $wrench \rightarrow WENCH$	$d$ rama $\rightarrow$ DMANA $parent \rightarrow PANAET$



Fig. 6. Experiment 1: Distribution of responses on target sequences (expressed in percentages) for Case FM and Case BWN.

Thus, the results of Experiment 1 indicate that digraphs and clusters are represented in a manner that is sufficiently distinct that they can be affected differently by a graphemic buffering deficit. More specifically, the results are consistent with the view that digraphs are represented as single units while clusters are not.

## Experiment 2: Analysing transposition errors in vowel digraphs

As indicated in the Introduction, even if digraphs are units at some level of the spelling process, such units will need to be 'unpacked' and their constituents serially produced. This involves the specific challenge of selecting and producing the constituents in their correct relative order. Although earlier analyses did not reveal any specific ordering difficulties for consonant digraphs (see General Discussion), preliminary evidence suggested that BWN produced a particularly high rate of transposition errors on vowel digraphs. Therefore, BWN and FM's spelling of vowel digraphs was investigated further.

#### Methods

For BWN, we prepared two sets of word pairs to examine the spelling of vowel digraphs and clusters. Within each set, the word pairs were matched for length and the position of the critical segments (e.g., REACH/REACT; DAIRY/DIARY; LOIN/LION; FAINT/GIANT). For one of the lists, words were also matched for frequency, while for the other list they were not. The results for the two lists were virtually identical (which is unsurprising given the general absence of a word

frequency effect on BWN's spelling) and therefore the results for the two lists are combined for the analyses reported below (total  $n = 266$  words, 133 of each type).

As indicated earlier, there were not enough instances of vowel clusters in FM's corpus to compare the performance of digraph vowels with matched control clusters. Nevertheless, we will present his performance on a set of 78 words with vowel digraphs (e.g., 'beaver') and 28 words with vowel clusters (e.g., 'onion'), ranging in length from 5 to 9 letters.

#### Results

The results indicate that, in contrast to what was observed with consonant digraphs and clusters, BWN spelled vowel digraphs (74%; 99/133) significantly less accurately than vowel clusters (89%; 118/133) ( $\chi^2(1) = 6.1$ , p < .02). This occurred despite the fact that the digraphs had a higher average bigram frequency than control clusters (371 vs. 122;  $t = 2.96$ ,  $p < .006$ ). Furthermore, BWN's rate of transposition errors was quite striking for vowel digraph elements. In fact, 85% (29/34) of his errors to vowel digraphs were adjacent letter transpositions (e.g., "flaunt" $\rightarrow$  FLUANT; "again"  $\rightarrow$  AGIAN; "tabloid"  $\rightarrow$  TABLIOD). In contrast, transpositions made up only 53% (8/15) of BWN's errors to vowel clusters  $(\chi^2(1) = 4.2, p < .05)$ . Further evidence of the predominance of transpositions in vowel digraphs comes from an evaluation of errors on an additional set of 3200 words that BWN was administered for spelling to dictation during the same time period. Out of the 88 transposition errors he produced on this word set, 68% occurred on digraphs. Although this is not a controlled comparison of digraphs with other letter types, it is quite remarkable, nonetheless, especially if one considers that the vast majority of letters pairs in this 3200 word set are certainly not digraphs.

FM's performance with vowel digraphs does not follow the pattern observed in BWN. Although we could not match the two types of letter sequences, it is nonetheless noteworthy that there is no indication that vowel digraphs are more difficult than control clusters or than consonant digraphs. Indeed, FM spelled 75% of vowel digraphs correctly, as opposed to 32% of vowel clusters, an advantage consistent with what was observed with consonant digraphs. In addition, unlike BWN, FM produced only 5% transposition errors on digraphs and 4% on clusters. Possible reasons for these differences between FM's and BWN's performance are discussed below.

# General discussion

Our principal findings are that: (a) both FM and BWN spelled consonant digraphs significantly more accurately than clusters and (b) BWN produced significantly more transposition errors on vowel digraphs than on control vowel clusters.

With regard to the greater accuracy of consonant digraphs over clusters, is important to emphasize that this difference cannot be attributed to the bigram frequency of the target segments. In FM's case this is a straightforward conclusion as consonant clusters and digraphs were matched for frequency. In BWN's case a bigram frequency account is unlikely because, although for both consonants and vowels the digraphs were more frequent than the clusters, consonants yielded greater accuracy for digraphs than clusters, while for vowels the reverse pattern was observed.

We can account for findings a and b if we assume that digraphs are not represented as simple letter sequences but instead that they are represented as units with an internal structure that specifies their constituent letters and their relative order (see Fig. 1). Specific support for this proposal is as follows. First, evidence of the unitary nature of digraphs comes from: (a) the finding of superior performance with digraphs than clusters and (b) the tendency for digraphs to retain their ''unitary'' character as evidenced by the fact that they are less likely than clusters to be broken up through the deletion or non-adjacent movement of constituents. Second, evidence of the internal complexity of digraphs comes from BWN's extremely high rate of transposition errors for vowel digraphs. These errors indicate that the relative ordering of the digraph's constituents is more vulnerable to disruption than the relative ordering of any other letter pairs.

Although this proposal can account for the primary findings of this investigation, a number of outstanding questions remain. First, we found that BWN was more accurate with consonant digraphs than clusters while the reverse was observed for vowels. Furthermore, vowel digraphs gave rise to transposition errors while consonants digraphs did not. This contrast between consonant and vowel digraphs may result from differences in the orthotactic legality of the letter pairs that would result from letter transposition in each case. In fact, the transposition of the elements of consonant digraphs generally results in orthotactically illegal or highly dispreferred sequences, while this is not the case for consonant clusters. For example, transpositions of digraphs such as  $CH \rightarrow HC$  or  $CK \rightarrow KC$  are unattested in English and even PH  $\rightarrow$  HP and  $SH \rightarrow HS$  are extremely unusual. However, transpositions within consonant clusters such as  $BR \rightarrow RB$ ,  $GR \rightarrow RG$  or  $TR \rightarrow RT$  are all attested and fairly common (mean bigram frequency  $= 117$ ; Mayzner and Tresselt, 1965). In contrast, transpositions within vowel digraphs and clusters are legal and quite common (e.g.,  $OI \rightarrow IO$ ,  $AI \rightarrow IA$  or  $OU \rightarrow UO$ ), with the mean bigram frequency for the transpositions of digraphs and clusters equal to 83 and 165, respectively. Thus, with regard to the orthotactic acceptability of transposition errors for digraphs vs. clusters, there is a very striking asymmetry for consonants, but not for vowels. This may result in consonant digraphs being ''protected'' against transposition errors.

A second question concerns the fact that transpositions were observed for vowel digraphs in BWN's case but not in FM's. This may reflect differences in the extent or severity of their deficits. For example, if one assumes that graphemic buffering involves both the activation and the serial selection of letters (Houghton et al., 1994; Rapp and Kong, 2002), then it may be the case that BWN's deficit affects both the activation and selection components, while FM's affects only

the activation of graphemes. As discussed in the Introduction, the serial selection of letters that form part of a digraph may be particularly error-prone if one assumes that the grapheme unit would need to be ''unpacked''. This view of digraphs as units which, subsequent to activation, must be unpacked, resembles proposals regarding the representation of compound words (e.g., Badecker, 2001). Consistent with this view and with the observation of letter transpositions in BWN's spelling of vowel digraphs, transpositions of the elements of compounds have been reported both in normal slips of the tongue (Fromkin, 1973) as well as subsequent to neural injury (Badecker, 2001).

A final question concerns the representational relationship between digraphs and double letters, such as BB in RABBIT. As indicated, an earlier study of FM (Tainturier and Caramazza, 1996) showed that doubles were produced more accurately than digraphs and also yielded different error patterns. For example, FM often substituted double letters with other doubled letters (e.g., rabbit  $\rightarrow$  RAPPIT), but this was not observed for digraphs. These various observations can be accommodated if one considers that while digraphs and doubles are both represented in a unitary manner at some level of representation and processing, they differ in terms of subsequent processing. Doubles require a process that recognizes the doubling feature and produces a repetition of the letter to be doubled, whereas digraphs require a process that identifies their constituents and their ordering. These processes may be differentially affected by neural injury, leading to the various patterns of impairment that have been attested and which have provided such insight into the nature and internal organization of orthographic representations.

# Summary and conclusions

In sum, we have reported two cases of acquired dysgraphia that reveal that digraphs are represented in a different manner than other grapheme sequences. In order to account for the pattern of results, we have proposed that digraphs are represented as units with an internal structure that specifies the identity and ordering of their constituents. This study provides the first empirical evidence in support of this proposal. More generally, these findings further strengthen the view that the orthographic representations used in spelling are complex mental objects rather than simple linear representations of letter strings.

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