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Serial Order Effects in Spelling Errors: Evidence from Tv Dysgraphic Patients

Niels O. Schiller¹, Jennifer A. Greenhall, Jennifer R. Shelton and Alfonso Caramazza

Cognitive Neuropsychology Laboratory, Department of Psychology, Harvard University, Cambridge, MA 02138, USA

¹Present address: Universiteit Maastricht, Faculty of Psychology, Department of Neurocognition, PO Box 616, 6200 MD

Maastricht, The Netherlands and Max Planck Institute for Psycholinguistics, PO Box 310, 6500 AH Nijmegen, The Netherland

Abstract

This study reports data from two dysgraphic patients, TH and PB, whose errors in spelling most often occurred in the final part of words. The probability of making an error increased monotonically towards the end of words. Long word were affected more than short words, and performance was similar across different output modalities (writing, typing and oral spelling). This error performance was found despite the fact that both patients showed normal ability to reposite the same words orally and to access their full spelling in tasks that minimized the involvement of working memory. Pattern of performance locates their deficit to the mechanism that keeps graphemic representations active for further processing, and shows that the functioning of this mechanism is not controlled or 'refreshed' by phonological (or articulatory) processes. Although the overall performance pattern is most consistent with a deficit to the graphemic buffer, the strong tendency for errors to occur at the ends of words is unlike many classic 'graphemic buffer patients whose errors predominantly occur at word-medial positions. The contrasting patterns are discussed in terms of different types of impairment to the graphemic buffer.

Introduction

Spelling errors of normal adults (e.g. Wing and Baddeley, 1980) as well as of brain-damaged patients (e.g. Caramazza and Miceli, 1990; Rapp and Caramazza, 1997) are not randomly distributed. Instead, they follow certain distributions, which can indicate where in the language production system the error occurs. For example, Wing and Baddeley (1980) investigated the spelling errors of normal subjects and found that slips of the pen were more likely to occur in the middle than at the beginning or end of words. Since their subjects wrote the words correctly at other times, the errors were assumed to have arisen after the orthographic representation in the lexicon had been accessed. Wing and Baddeley (1980) attributed the locus of the errors to the graphemic buffer, i.e. 'a working memory system which temporarily holds graphemic representations for subsequent, more peripheral processes (e.g. allographic conversion)' (Caramazza and Miceli, 1990, p. 257-8). The serial position effect of the spelling errors has been interpreted as resulting from interference between neighboring letters in the graphemic buffer (Wing and Baddeley, 1980). Since medial letters of a word have more neighbors than letters at the periphery of a word, they are more prone to being misspelled, resulting in a bow-shaped error distribution.

There are several neuropsychological studies repor patients who showed a similar bow-shaped distribution spelling errors. For instance, patient LB, studied Caramazza (Caramazza et al., 1987; Caramazza and Mi 1990), exhibited a bow-shaped distribution of errors in spelling of both words and non-words. The same distribu of errors was found in oral spelling, but oral repetition words was unimpaired, where LB repeated each word be writing it down. Thus, the (sublexical) phonological sys was unimpaired and LB's spelling deficit was localized the graphemic buffer level (see also Miceli et al., 19 1987; Posteraro et al., 1988; Hillis and Caramazza, 19 Kay and Hanley, 1994; McCloskey et al., 1994; Taintu and Caramazza, 1994; Jónsdóttir et al., 1996; Freedi and Martin, 1999). Two patients (reported by Hillis Caramazza, 1989), ML and DH, however, showed a st deviation from the normal bow-shaped distribution of en In both cases, the distribution was bow shaped, but skey in opposite directions. Whereas ML's spelling errors occur primarily at the beginnings of words, DH showed an incre in errors towards the end of words. However, the over spelling patterns found with both patients were compat with damage to the graphemic buffer. The authors propo

Correspondence to: Niels O. Schiller, Max Planck Institute for Psycholinguistics, PO Box 310, 6500 AH Nijmegen, The Netherlands. Tel: +31 24 352131 Fax: +31 24 3521213; e-mail: niels.schiller@mpi.nl or n.schiller@psychology.unimaas.nl

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that the skewed distribution of spelling errors is a variation of the normal bow-shaped pattern that is modulated by a mild hemispatial attentional deficit (neglect).

Caramazza proposed a set of criteria for identifying selective damage to the graphemic buffer (Caramazza et al., 1987). (1) Patients with this type of impairment should exhibit similar patterns of spelling errors for words and nonwords. (2) They should perform at comparable levels on a variety of tasks (e.g. written naming, writing-dictation, delayed copying, etc.) and across different output modalities (oral and written spelling, typing, etc.). (3) Their error patterns should not be affected by lexical factors such as word class, frequency and concreteness because temporary storage in the graphemic buffer is supposed to follow access to the orthographic representations in the lexicon. (4) The errors themselves should include substitutions, deletions, insertions and transpositions of letters. These types of errors would reflect the degradation of the spatially encoded, accurate graphemic representation of the intended word. Whole-word substitutions, however, should not be found (except as these may result by chance from grapheme substitutions, deletions or insertions). (5) Word length should show an effect on the error pattern, since, with increasing word length, the number of letters in the buffer increases and therefore the probability of making a spelling error

Katz (1991) reported a patient, HR, whose performance followed the above criteria, but who showed a different pattern of error distribution: the number of errors increased monotonically from the beginning to the end of a word. The author accounted for this error distribution by claiming that HR's impairment was due to a rapid decay of letter identity information in the graphemic buffer. Letters that occurred towards the ends of words had to be held longer in the buffer than letters at the beginning and were therefore more likely to be misspelled. In support of this hypothesis, Katz reported data from a backward spelling task in which letters at the end of a word had to be produced before letters at the beginning (Katz, 1991). HR produced fewer errors on the letters at the end of the word than he did in normal forward spelling, supporting the 'decay-of-information' hypothesis. Clearly, HR's performance depended on writing direction (left-right versus right-left). A similar case, CH, was reported by Bub (Bub et al., 1987).

Recently, Ward and Romani reported the case of patient BA, who also showed a monotonically increasing serial position effect in her error distribution (like HR and the patients we are reporting in this paper) (Ward and Romani, 1998). BA produced initial letters more accurately than medial letters and medial letters more accurately than final letters. In comparison to previous interpretations, Ward and Romani (1998) argued that BA's serial position effect in the spelling errors was due to incomplete activation of the orthographic representations in the lexicon rather than damage to the graphemic buffer. Their patient, unlike HR (Katz, 1991), did not show the same error distribution in the

backward spelling task as in the forward spelling task. For example, BA misspelled the word bone backward as INOB, i.e. she made an error on the first spelled letter. This showed that her errors were related to the serial order position in the abstract word form and not to the order in which she wrote the letters, prompting Ward and Romani to argue that this result does not support the hypothesis of a deficit to the graphemic buffer.

In this paper, we present data from patients TH and PB, who show a 'linear' serial position effect similar to patients BA and HR. TH's and PB's pattern of performance is important for (at least) two issues regarding spelling deficits: (1) understanding the contrasting error patterns displayed by patients (i.e. bow-shaped error pattern versus 'linear' error pattern) and (2) understanding the underlying nature of the deficit that results in the specific error pattern displayed by patients like TH, PB, BA and HR (i.e. contrasting hypotheses presented by Katz, 1991 and Ward and Romani, 1998). In addition, TH's and especially PB's performance may provide information regarding the role of phonology in spelling. Jónsdóttir claimed that intact phonological processing could help keep the orthographic representations active while the patient is engaging in the sequential output process of spelling (Jónsdóttir et al., 1996). In contrast to patient BA, who 'was virtually unable to produce any spoken language' (Ward and Romani, 1998, p. 191), TH and PB are fluent and repeat words perfectly, allowing us to test to what extent phonological support can influence spelling performance.

Case report 1: TH

TH is a 63-year-old, left-handed male who had a cerebro-vascular accident in 1982. A CT scan performed 2 years post-onset revealed an old infarct in the territory of the left middle cerebral artery. Unfortunately, no photographic documentation of the CT scan is available. TH presents with a mild lower right facial weakness, a plegic right upper arm and a paretic right leg. He also has reduced pin-prick sensation over the right side of his body. Visual fields are full on confrontation. Although TH has hemiparesis of the right side, he functions normally in daily life. He drives a car, works with a computer at home and uses e-mail. TH attended college for 1 year and worked for more than 40 years as a clerk, but is now retired. He reports that he always enjoyed reading and continues to read a daily newspaper.

Th's working memory system is impaired. He has a digit span of only four digits forward and two digits backward. Digits were given at a rate of one per second. In the five digits forward condition, his response contained all target digits, but the order was not correct. Th showed no signs of neglect on a number of standard tasks such as drawing from memory, search tasks and line bisection. His speech is fluent and intelligible, and he can follow conversations. However, occasionally he makes semantic errors in oral (and written) spontaneous language production (e.g. grandson → son, Thanksgiving → Easter). His comprehension is normal to

mildly impaired. He performed flawlessly (12/12 correct) in an auditory word-picture matching task, but showed mildly impaired performance (15/16; 94% correct) in an auditory sentence-picture matching task. TH did not make any errors in auditory or visual lexical decision tasks (10/10 correct in each modality). His single-word and non-word repetition is unimpaired (50/50 correct).

TH cannot read non-words aloud, indicating damage at some level of the grapheme—phoneme conversion process. Overall, his single-word reading is fairly good, but not perfect (2059/2219 = 93% correct). Th's reading performance is reported elsewhere (Rey *et al.*, unpublished results).

In oral picture naming, TH exhibited mild impairments (485/533 = 91% correct). For instance, on the Philadelphia Naming Test (Roach *et al.*, 1996), he performed similarly to other patients of his age (see Ruml *et al.*, 2000), but significantly worse than normal subjects (see Roach *et al.*, 1996). His phonological output processes, however, were unimpaired, as indicated by his reading aloud of the same picture names (429/435 = 99% correct) and by his perfect repetition (see above).

In written picture naming, TH performed worse (383/531 = 72% correct). He made two morphological and 24 semantic errors (e.g. duck \rightarrow geese). In addition, he made many spelling errors (e.g. mushroom \rightarrow rushmuck, television \rightarrow televissor). Interestingly, he also made spelling errors on semantic substitutions (e.g. artichoke \rightarrow caulflower, strawberries \rightarrow rasberrey). However, discounting spelling errors, his naming performance was similar for oral and written production.

TH does not seem to have specific grammatical problems, but this aspect has not been studied in detail. He participated in this research project from June 1998 to November 1999. After a general screening period, we focused our testing on his spelling abilities. During the testing period, his performance was considered to be stable.

General spelling abilities

Across all tasks, TH spelled 1858 words (oral spelling, writing to dictation, written picture naming, typing to dictation, spelling with letter cards). We will first give a general overview of his spelling abilities and then discuss more specific tasks.

TH was given the Johns Hopkins University (JHU) Dysgraphia Battery (Goodman and Caramazza, 1987), which includes the following tests: part-of-speech, concreteness, regularity, phoneme-grapheme conversion probability (i.e. the probability of spelling a word correctly by applying non-lexical phoneme-grapheme conversion) and word length. The phoneme-grapheme conversion probability test consists of a list of words that vary with respect to the probability with which a particular phoneme is transcoded into a particular grapheme. For instance, the phoneme /t/ is always transcoded as <t> in spelling, whereas /s/ can be transcoded as the graphemes <s> or <c>, varying in probability. Table 1

displays TH's performance across all tasks and demonstrates that he showed some effects of syntactic word class (part-of-speech), with nouns and function words spelled better than verbs and adjectives ($\chi^2 = 10.6$, P < 0.05). He spelled concrete words better than abstract words ($\chi^2 = 7.0$, P < 0.05), and high-frequency words were spelled better than low-frequency words ($\chi^2 = 7.4$, P < 0.05). However, TH did not show an effect of regularity nor of phonemegrapheme conversion probability. Most importantly, TH showed a strong effect of word length, decreasing from 71% correct for four-letter words to only 36% correct for eight-letter words.

TH's performance on writing pronounceable non-words was tested using two different lists of non-words. The first one contained non-words that were four or five letters in length, where TH spelled only 3% correctly (2/70). However, in 53% of the cases he got at least the first letter correct, showing that he could convert some phonological information into graphemes. For 47% of the non-words, TH made lexicalization errors, most of them being phonologically similar to the target (e.g. suft \rightarrow soft or manch \rightarrow ranch). The second list included 20 shorter non-words not exceeding three letters (10 CV, 10 CVC, where C is consonant and V is vowel). TH performed much better on this second list. He spelled 50% of the non-words correctly; on 85% of the nonwords, he got the first letter correct, and on 75% even the first two letters were correct. This test showed that he could convert phonological information into graphemes, at least to some degree. Furthermore, the error pattern on non-words resembled the error distribution on words with more errors at the end than at the beginning of words.

TH was also tested in a delayed copying task where he first looked at a string of letters printed in capital letters; the string was then covered and TH was asked to write it down in script form. This test was carried out to see whether knowledge about the spelling of a string influenced his spelling performance. The list of 62 items (4–7 letters in length) contained 20 non-words. Altogether, TH scored 84% correct (52/62). Only two of his errors occurred on nonwords (90% correct), showing that it is not the lexical status per se that is responsible for his spelling errors. However, since TH was asked to transcode the letters from capitals into script in the delayed copying task, it may be possible that the error pattern reflects problems at the allographic level rather than at the orthographic/graphemic level. This possibility was tested in a delayed copying task in which TH was asked to copy a new set of 40 words (5–7 letters in length) from printed capital letters into written capital letters. The results of this task were similar to his previous performance in delayed copying: overall, TH spelled 73% of the words correctly and he made similar types of errors as before, e.g. substitutions, deletions, insertions, etc., indicating that his spelling problem is probably not due to impaired allographic conversion. Furthermore, the letters he wrote were always well formed.

In general, TH was aware of his spelling errors, and he

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Table 1. TH's performance in various spelling tasks of the JHU Dysgraphia Battery

Word list	Sublist	% correct	71.	χ^2	P	Example target	Example error
Part-of-speech				10.6	< 0.05		
Luit of Special	Nouns	82	23/28			motel	motol
	Verbs	64	18/28			learn	leane
	Adjectives	43	12/28			strict	striqt
	Functors	75	15/20			while	wild
Concreteness				7.0	< 0.05		
CONCLORUNGS	Concrete	71	30/42			kitchen	kithen
	Abstract	43	18/42			moment	memey
Phoneme–grapheme conversion probability			0.1	>0.10			
2 1101101111 P. o.L.	High	77	23/30			twin	trim
	Low	73	58/80			fruit	friut
Word length				4.4	< 0.05		
1,014,1016	Four-letter	7 1	10/14			edit	abit
	Five-letter	57	8/14			igloo	aggle
	Six-letter	64	9/14			fumble	fulle
	Seven-letter	64	9/14			absence	absene
	Eight-letter	36	5/14		,	language	langued
Word frequency (collapsed across various sublists)				7.4	< 0.05		
1	HF	67	74/111				
	LF	49	54/111				

Lexical factors, such as frequency, syntactic word class (part-of-speech) and concreteness affected TH's performance, indicating that mild damage to the lexical system is a contributing factor to his spelling performance. However, phoneme-grapheme conversion probability did not affect his spelling. Furthermore, his spelling errors were not phonologically plausible (e.g. half → helf; idealist → ilealist). He made very few semantic errors (less than 1%), i.e. categorically or associatively related lexical substitutions, possibly including a spelling error. Word length was a major determinant of performance and his errors in spelling mostly consisted of neologisms resulting from letter substitutions, deletions, additions, and transpositions in the middle and end parts of the response. In contrast, the number of lexical substitution errors in spelling was only 11 (out of 1858 words TH had to spell; 0.6%). However, even most of these 11 lexical substitutions maintained some visual similarity to the target, e.g. solve \rightarrow folder.

mentioned this during spelling. However, when asked to correct his errors, he could not do so nor could he indicate where in the string the error(s) was (were) located. He often commented: 'That doesn't look right' or 'I know it's not right'. This is not surprising given the fact that TH performed flawlessly in lexical decision tasks (see above). Sometimes, however, he appeared unaware of his errors while writing. When he was asked to read a list of 68 words interspersed with 25 of his own non-word errors (taken from misspelled words of the JHU Dysgraphia Battery; see below), he recognized the misspelled strings as non-words, but could not read them. When asked to read the non-words, he either confabulated something (e.g. loster \rightarrow losser) or, in 40% of the non-words (10/25), he made a lexicalization error and came up with a visually and/or phonologically similar word (e.g. fush \rightarrow fish). He was able to read the existing words in this list without any problem (96% correct), reflecting his overall good reading abilities.

Specifying TH's spelling deficit

The fact that he generally does not make semantic errors in reading, his inability to make complete use of phonemegrapheme conversion, and his lexical impairments including effects of word frequency, part-of-speech and concreteness in written spelling, and the fact that he makes morphological and semantic errors in written and spoken output, would

classify TH as a 'deep dysgraphic' patient according to the criteria given in Bub and Kertesz (Bub and Kertesz, 1982). Actually, Bub and Kertesz's (1982) patient JC performed quite similarly to our patient TH, except that JC was able to read pronounceable non-words whereas TH could not. TH is even more similar to the graphemic buffer patient VS studied by Nolan and Caramazza (Nolan and Caramazza, 1983). TH shows a relatively good overall reading performance (93%) correct) compared to his relatively poor overall spelling performance (62% correct). Therefore, TH's data support the claim that phonological processing for reading is functionally separate from phonological processing for writing (Bub and Kertesz, 1982; Nolan and Caramazza, 1983). TH's lexical impairments, however, seem to be independent of his spelling deficit. This view is supported by the fact that even in written picture naming his semantic substitutions contain spelling errors, thus indicating that TH can access the semantics of a lexical item correctly, but when he tries to retrieve the orthographic representations, either they are damaged or the correctly retrieved orthographic information is not processed normally at the level of a graphemic buffer. However, whether the spelling problem arises in transferring information from the orthographic representations into the graphemic buffer, whether the graphemic buffer itself is damaged, or whether the deficit is in the transfer of information out of the graphemic buffer to more peripheral output processes, we cannot say.

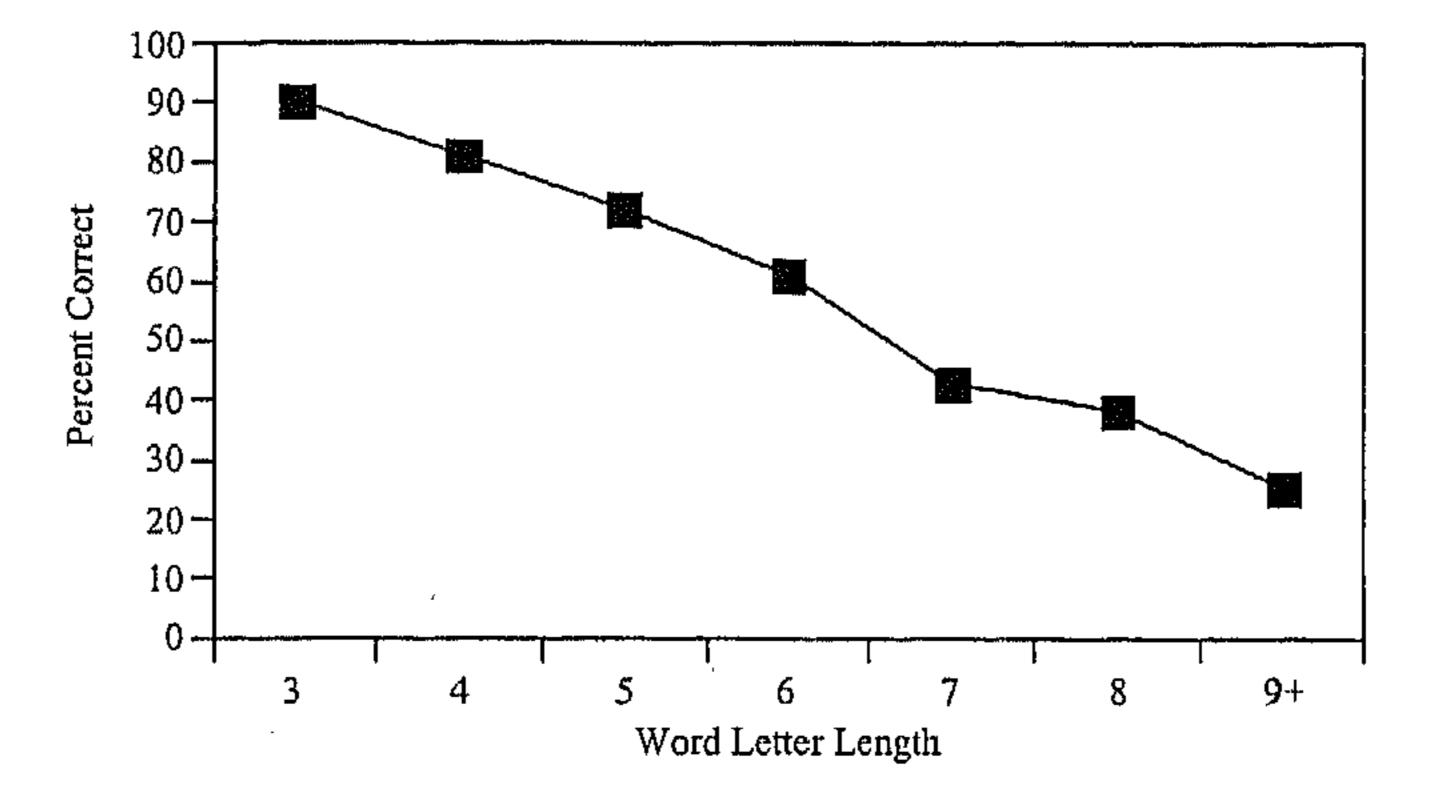


Fig. 1. Proportion of correct responses as a function of word length for TH.

Written spelling analysis

Altogether, TH spelled 1858 words. Figure 1 shows the proportion of correct responses as a function of word length, and it is quite evident that TH performs much better on shorter words as compared to longer words. Whereas he is over 90% correct on three-letter words and still over 80% correct on four-letter words, TH's performance falls to less than 30% correct on words that have nine letters or more. This performance is similar to that of LB (Caramazza et al., 1987), who showed an even more pronounced wordlength effect.

To investigate further the nature of TH's serial position effect in spelling errors, new word lists were devised to assess various factors thought to have an influence on the serial position effect in spelling. The results of his spelling performance on each of these tests are reported separately

Short versus long words

The word-length effect reported above was found with the 'word-length list' (see Table 1) from the JHU Dysgraphia Battery. However, this list only contains 70 items. In order to assess TH's word-length effect further, we devised a new list of words, which varied word length across a broader range to test specifically whether TH would make more errors on long than on short words. This test includes a whole set of words that have at least eight letters, matched in frequency and word class to a set of shorter words.

Materials. Short words did not exceed two syllables (M = 1.6) and seven letters (M = 5.1); long words had at least three syllables (M = 3.2) or eight letters (M = 8.7). There were equally as many words from different syntactic classes in both sublists. Mean word frequency was lower for the short words (23 per million word forms) than for long words (34 per million word forms) as determined by CELEX (Baayen et al., 1995). There were 99 words in each of the two sublists. The complete list of 198 words was randomized and given to TH in a writing-dictation task over three different testing sessions.

Procedure. The procedure in this task and all of the subsequent written spelling tasks was as follows. The

experimenter said the target word aloud, TH repeated it, and then he wrote it down. In the rare event that TH repeated something other than the target word, the experimenter said the word again until TH correctly repeated it. After his spelling attempt, TH was required to say the target word again.

Results. Although word frequency was higher for the long words, TH made significantly more errors on the long words than on the short ones. He was correct on 64% of the short words (63/99), but only on 30% of the long words (30/99) $(\chi^2 = 22.2, P < 0.05).$

To analyse the proportion of his spelling errors at each letter position across words differing in length, the distribution of errors was normalized according to the principles proposed by Wing and Baddeley (Wing and Baddeley, 1980). This normalization procedure divides each word into five abstract letter positions (1–5). Each abstract letter position contains one or more letters of the target word, depending on its length. The letters of the target word are assigned to the abstract letter positions in such a way that a symmetrical structure is maintained (see Caramazza et al., 1987 for details). The errors are calculated according to the criteria stated below and then divided by the total number of letters in a specific abstract letter position, thus yielding a proportional measure of the error distribution normalized for word length.

The error scoring followed the principles outlined in Caramazza and Miceli with some modifications (Caramazza and Miceli, 1990, p. 250). Deletions and substitutions were scored one point; insertions were assigned 0.5 points to the positions before and after the insertion. Letter shifts were assigned 0.5 points to the original letter position in the target word and 0.25 points to the positions before and after the insertion. Letter exchanges were assigned 0.5 points to each of the two positions from which the exchanged letters originated.

Furthermore, the following general principles were applied. First, target word and response were arranged in such a way as to maximize the segmental overlap between them. Second, the scoring was such that the error points were minimal for a given misspelled word. That is, whenever it was possible to score a word with multiple errors in different ways, the one with the least error points was chosen.

The normalized error distribution collapsed across short and long words revealed a monotonic increase in the relative proportion of error points from the first to the fourth position (13.3, 20.2, 25.0, 27.1) and a slight decrease at the fifth position (22.8). TH was later asked to read this list of words, which he did nearly perfectly (196/198 = 99%) correct), demonstrating that he knew the words.

Discussion. TH's performance on a list of short versus long words supports the linear serial position effect in his spelling errors. Short words were spelled significantly better than long ones, and he made more spelling errors towards the end of words than at the beginning. TH was always correct when repeating the to be spelled word after his spelling attempt. In spite of this, he made many errors in spelling, especially on the long words. The fact that he could repeat the word after his spelling attempt implies that he rehearsed or always kept the target word in immediate memory. Yet, this phonological information did not improve his written spelling.

Morphologically simple versus complex words

One factor that was confounded with word length in the list of short versus long words was the morphological complexity of words. Morphologically complex words, e.g. derived or inflected words, were on average longer than simple, monomorphemic words. Therefore, the fact that TH's spelling performance was worse for long than for short words may in fact have been a morphological effect. It could be that his morphological system is impaired such that complex words are more difficult for him to write than simple words. To test this hypothesis, we constructed another list of words, manipulating the factor of morphological complexity while trying to keep all other factors constant.

Materials. Altogether, there were 198 words in this list, half of them simple (i.e. monomorphemic) with a mean length of 2.8 syllables and 7.0 letters, the other half complex (i.e. inflected or derived), on average 2.8 syllables and 6.4 letters long. The number of words from different syntactic word classes was equal in both sublists and both types of words had a mean frequency of occurrence of 18 per one million word forms as determined by CELEX.

Results. TH was correct on 46% of the morphologically simple words (46/99) and 55% of the morphologically complex words (54/99). The normalized distribution of errors followed the same pattern as in the previous spelling tasks: there was a linear increase from the beginning to the end of words (error proportions: 10.9, 15.0, 19.5, 22.4 and 29.1 for the first to the fifth normalized letter position, respectively). As with the previous list, TH read these words nearly perfectly (192/198 = 98% correct).

Discussion. In general, morphological complexity did not have an effect on TH's spelling performance. He performed slightly better on the complex than on the simple words. This shows that morphological complexity is not responsible for his marked word-length effect. The normalized error distribution demonstrated that he made more errors towards the end of words than at the beginning. Thus, TH seems to display a similar, monotonically increasing error pattern as HR and BA (instead of the bow-shaped error pattern known from graphemic buffer patients such as LB or AS). We will discuss these contrasting error patterns in more detail in the General discussion.

Overall spelling analysis

The normalized error distribution for all of TH's written spelling errors (n = 1817; multiple spelling errors per word were counted separately) on the whole corpus of 1858 words

is depicted in Fig. 2D. The whole corpus includes the JHU Dysgraphia Battery sublists, the written picture naming lists and the two lists reported in the last two sections. As can be seen, the pattern of errors TH made increased monotonically from the beginning towards the end of words.

Morphological boundaries

Badecker reported the case of DH, a graphemic buffer patient who showed a marked effect of morphological boundaries on the error distribution for the spelling of morphologically complex words (Badecker *et al.*, 1990). We looked at whether this was also the case for TH. To this end, the error distribution in misspelled compounds from a list including 62 compounds was analysed.

Results and discussion

TH did not show an effect of morphological boundaries in his spelling errors. His relative error proportions on the normalized positions were 5.3, 6.9, 15.3, 15.7 and 13.9 from the first to the fifth position for the first part of compounds. With respect to the second part of compounds, his relative error proportions were 12.8, 10.8, 12.0, 16.5 and 18.6. In fact, when both parts were combined and analysed as a single word, a monotonically increasing error pattern became visible (19.0, 29.4, 36.7, 37.6 and 31.5). Unlike DH, TH does not seem to be sensitive to morphological boundaries of compound words, at least not in spelling. We will discuss this point further when we report the results of a similar analysis for our second patient PB.

Graphosyllabic structure

Caramazza and Miceli suggested that graphemic representations consist of more structure than a linearly ordered string of graphemes (Caramazza and Miceli, 1990). The re-analysis of patient LB showed that his spelling errors were constrained by graphotactic principles such as graphemic consonant, graphemic vowel and graphemic syllable. LB respected the C/V status of the substituted letter in virtually all (99.3%) letter substitution errors (736/741). Furthermore, his performance was significantly different on geminate and other CC clusters, indicating different graphosyllabic representations. However, LB's errors did not seem to follow phonological principles as his errors violated basic phonological constraints such as the sonority sequencing generalization. On the basis of the error pattern found in LB, Caramazza and Miceli (1990) proposed a multi-tiered graphosyllabic orthographic lexical representation. The multidimensional structure of graphemic representations they suggested includes the following four tiers: a grapheme tier specifying the identity of the graphemes of a word, a quantity tier representing the quantity of the specified grapheme identities (e.g. single or double letter), a CV tier for the C/V status of the grapheme and a graphosyllabic tier specifying the graphosyllabic bound-

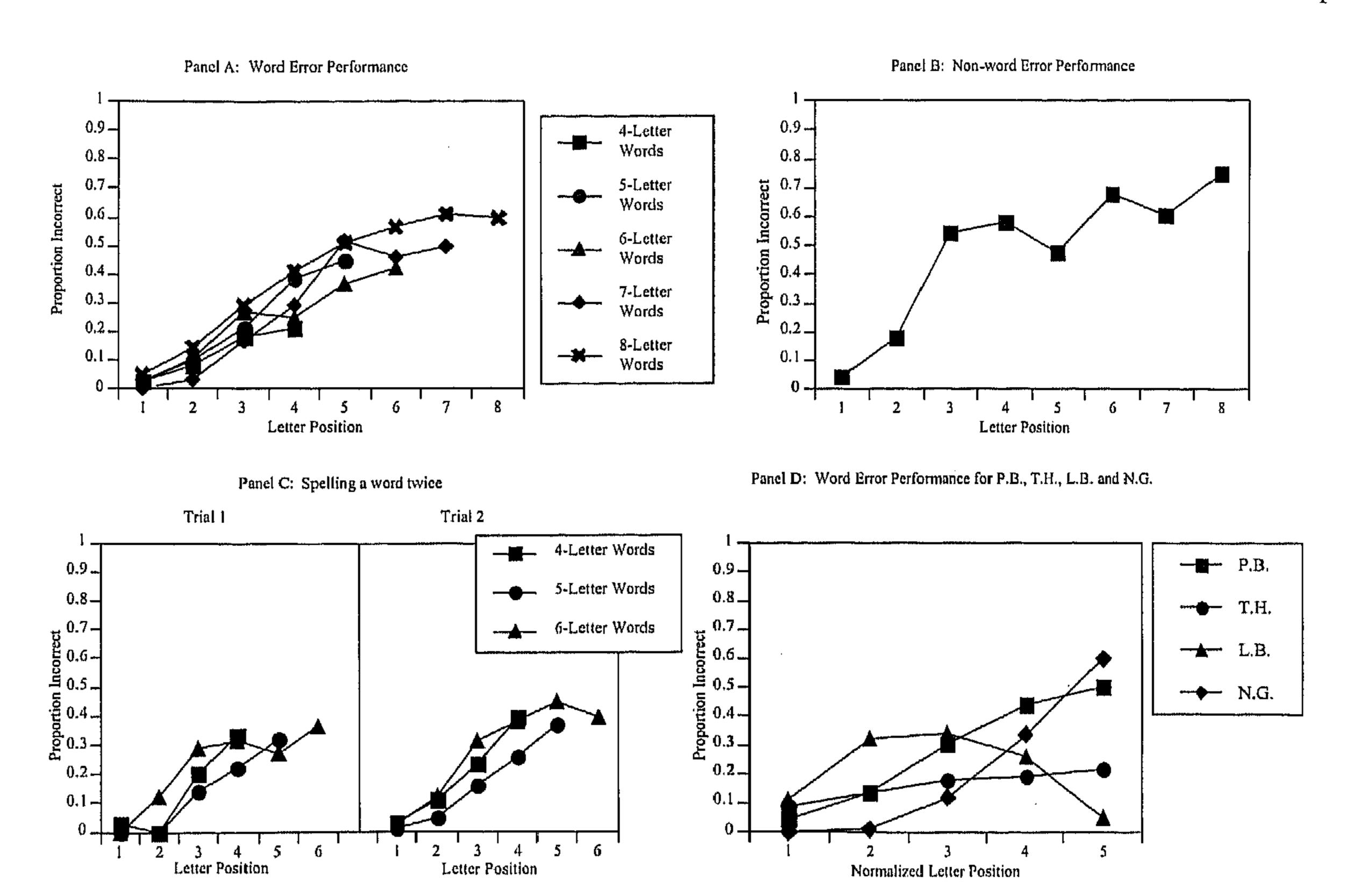


Fig. 2. Serial position performance in writing-to-dictation words and non-words. The following procedure was used in all writing-to-dictation tasks. First, the tester said the word aloud; next, PB repeated it to ensure correct auditory comprehension and then attempted to spell the word on a single, separate sheet of paper; finally, she repeated the word again. (A) The percentage of errors for each letter position for words of lengths four, five, six, seven and eight letters. These functions are based on very large numbers of spelling trials for each word length. There were 204 four-letter words, 270 five-letter words, 178 six-letter words, 107 seven-letter words and 135 eight-letter words. Very few errors were made for the first letter and errors increased for later letter positions. The distribution of spelling errors as a function of letter position in six-letter words in a control aphasic patient (MS) of comparable age and education to PB was 0.3, 4.2, 6.1, 3.7, 5.7 and 5.3% for positions 1-6, respectively. (B) The percentage of errors for each letter position for non-words. Non-words were not separated by letter length because English does not allow a one-one mapping between phonology and orthography and, thus, we could only approximate the length of the target response by the subject when asked to spell a non-word. For example, FOIT could be spelled as FOIT, PHOIT or FOYGHT or PHOIGHT, leading to four-, five-, six- or seven-letter length responses. The error total of each letter position was divided by the approximated number of words with letters at that position (n = 83, 83, 83, 83, 66, 43, 14, 3). Nonetheless, it can be noted that the serial position curve for non-words is similar to that for words. (C) PB's serial position performance in spelling a word twice. She was asked to spell a word, which was covered as she wrote it, and then had to immediately rewrite it. The profiles of performance for the two spelling trials are very similar; she spells the beginning of the word much better than the end of the word, and errors increase as a function of left-right position. The stimuli were four- (n = 33), five- (n = 34) and six-letter (n = 33) words. The 100 words were spelled twice. (D) A comparison of normalized serial position curves for TH and PB with two prototypical cases of damage at the level of graphemic representations: patients LB and NG. Patient LB shows the inverted-U function commonly found for many dysgraphic patients with damage to the graphemic buffer. This profile of performance indicates damage to the graphemic representations held in the buffer. Patient NG shows the classic word-centered profile of errors for patients with word-centered neglect: errors occur on the left or right of center (depending on the site of lesion) of the word. This pattern of performance suggests damage to a spatially specific mechanism for the allocation of attention to graphemic representations.

aries of a word. The analysis of JH's (Kay and Hanley, 1994) written spelling errors supported the view that consonants and vowels are marked distinctively in the graphemic representation (see also Cubelli, 1991). This can be seen as further evidence for Caramazza and Miceli's (1990) notion of a multi-tiered orthographic representation that not only encodes the identity and serial position of a letter, but also the C/V status of letters (see also McCloskey *et al.*, 1994).

To investigate whether TH respects the double-letter status in his spelling errors, he was administered a letter quantity list consisting of four- and five-letter monosyllabic words, some of which are spelled with a double letter, such as steel or skull. This list was administered to test whether or not his spelling errors honored graphosyllabic principles. TH's overall performance in this task was 80% correct. On the double-letter words, he scored 88% correctly, and in 6 of his 11 errors he maintained a double letter in the error (e.g.

sneer \rightarrow seeve, bleed \rightarrow breeb, floss \rightarrow fossol). Across all other spelling tasks, TH made 112 errors altogether on words that contained a double letter, e.g. lettuce or kangaroo. In 76 of these errors (68%), TH misspelled the target words with some sort of double letter. For instance, he misspelled lettuce as letten and kangaroo as kangeer. In contrast, TH inserted a double letter into target words that did not originally contain a double letter on 30 occasions only; considering insertion errors alone, this amounts to a proportion of 11% of these errors. This indicates that graphemic representations possibly encode the double-letter status in a word and that TH still had access to this type of information despite his spelling deficit (Caramazza and Miceli, 1990; McCloskey et al., 1994; Miceli et al., 1995; Tainturier and Caramazza, 1996). To investigate whether TH respected the C/V status of the substituted letters, we looked exclusively at those misspelled words that contained substitution errors only. Of 291 substitution errors, he respected the C/V status of the substituted letter 251 times (86%).

Although TH does not preserve the C/V and the double-letter status in his spelling errors to the same degree as LB (or other patients in whom this has been investigated; Kay and Hanley, 1994; McCloskey et al., 1994), he does not substitute letters randomly. Furthermore, his spelling errors are graphotactically legal, except for some very exceptional cases like knife \rightarrow fnive, and he tends to preserve letter length in his misspellings (see above). This supports the hypothesis that orthographic representations encode the C/V status, and thereby orthotactic constraints, as well as the double-letter status in words.

In summary, TH is a dysgraphic patient who showed a marked effect of word length (more errors on long than on short words). His spelling errors include all kinds of segmental errors, but hardly any whole-word substitutions. Although we cannot exclude damage to the lexical representations in the orthographic lexicon, TH's spelling deficit possibly involves the graphemic buffer. His spelling abilities were tested in different tasks and output modalities. For delayed copying and oral spelling, the error curves displayed a monotonic increase from the first to the fifth position, whereas for typing and backward writing he exhibited a bow-shaped error distribution. Most importantly, however, the error types were the same across tasks, and errors were not influenced by lexical factors such as word class or frequency. The distribution of TH's errors displayed a monotonic increase from the beginning to the end of words. TH could repeat without any problems the words he misspelled, demonstrating that his phonological output processes were intact. Nevertheless, he could not use the information from his phonological output buffer to improve his spelling difficulties. This dissociation is possibly due to the autonomy of phonological and orthographic representations in the lexicon. However, TH had problems spelling non-words because of his (partially) dysfunctional phoneme-grapheme conversion route. Therefore, it could be argued that this is the reason why he is unable to improve his spelling even though the phonological information is readily available to him. The second patient we present in this article, PB, is very similar to TH, except that her ability to spell non-words was better.

Case report 2: PB

PB is a 69-year-old, right-handed, highly educated woman who, as a consequence of a left-hemisphere stroke, has become hemiparetic, aphasic and dysgraphic. PB is a highly educated woman and has earned a BA in history, an MA in special education and was finishing her DEd (Doctor of Education) dissertation when she suffered a subarachnoid hemorrhage. In April 1992, a vascular MRI scan showed a superior/parietal left massive middle cerebral artery territory infarction with porencephalic changes and ventricular expansion. The frontal horn, occipital horn and the choroidal fissure were expanded, and the lenticulo-striate

territory was not spared by the infarct. At the time of testing (1996–1997), PB was classified as a Broca's aphasic with poor comprehension for syntactically complex sentences. Her ability to repeat single words (103/104 = 99% correct) and non-words (33/34 = 97% correct) was excellent, if mildly apraxic. Her reading performance is mildly to moderately impaired. Most of her reading errors are visually similar or morphologically related words (75% of all errors), but she also made occasional semantic errors. Her spelling performance, which is the focus of this paper, will be reported below in detail.

PB's spelling performance was also assessed with the JHU Dysgraphia Battery (Goodman and Caramazza, 1987). Overall, in writing to dictation, she spelled 39.3% or 351/894 of the words correctly (excluding three-letter words), indicating that her spelling was severely impaired. Table 2 shows her performance across all tasks and demonstrates that PB showed an effect of syntactic word class with nouns and function words spelled better than verbs and adjectives (P < 0.01). She spelled concrete words better than abstract words (P < 0.005) and high-frequency words better than low-frequency words (P < 0.001). Phoneme–grapheme conversion probability, however, did not influence her spelling behavior (P > 0.10). Most importantly, PB showed a marked word-length effect: while she wrote four-letter words with relatively high accuracy (93%), her performance decreased drastically (7%) for eight-letter words (P < 0.001). Compared to TH, this is an even more extreme decrease in performance. Overall, PB and TH performed very similarly in the spelling tasks of the JHU Dysgraphia Battery.

PB made letter substitutions, deletions, insertions and transpositions in the middle and end part of the words and non-words, but she almost invariably produced the beginning correctly (e.g. blast \rightarrow blik, member \rightarrow menting, volpet → volchs). Detailed investigation of this feature of her performance revealed that the probability of correctly producing a letter decreased monotonically from the beginning to the end of words. Her letters were consistently well formed. PB's ability to spell words orally could not be tested extensively because of an independent deficit in letter naming. PB's difficulty in naming letters was a source of considerable frustration to her, and she refused to be tested further on oral spelling. However, she was able to trace the letters correctly in the palm of her hand or on a table in front of her, and was able to spell with comparable performance to written spelling by arranging spelling cards.

PB was better able to spell non-words than TH. Whereas TH's ability to spell non-words correctly was limited to two-and three-letter non-words (50% correct; see above) [he was virtually unable to spell four- and five-letter non-words correctly (3% correct only; see above)], PB was occasionally able to spell six-, seven- and eight-letter non-words correctly. Although her overall error proportion was higher for non-words than for words (only 6/83 or 7.23% correct), PB exhibited the same monotonic increase in error rates by length for non-words as for words, showing that the nature

Table 2. PB's performance in various spelling subtests of the JHU Dysgraphia Battery

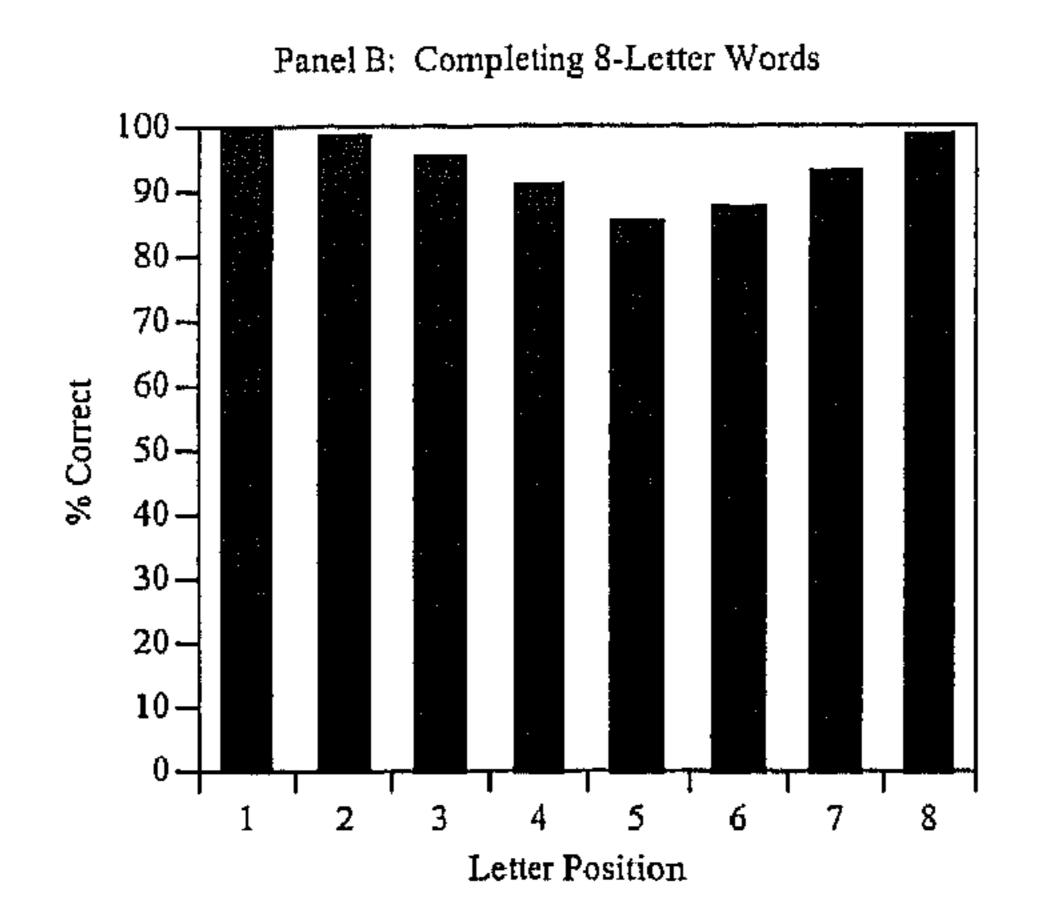
Word list	Sublist	% correct	\boldsymbol{n}	χ^2	. P	Example target	Example error
Part-of-speech			12.79	< 0.01	·		
_	Nouns	53.6	15/28			member	menting
	Verbs	25.0	7/28		•	begin	brington
	Adjectives	14.3	4/28			brisk	bruch
	Functors	50.0	10/20			though	thus
Concreteness (revised test)			9.64	< 0.005			
	Concrete	63.3	38/60			graduate	grandeth
	Abstract	35.0	21/60			support	suppote
Phoneme-grapheme conversion probability			1.45	>0.10			
	High	46.7	14/30			blame	blanch
	Low	59.5	47/79		1	fence	field
Word length			29.67	< 0.001			
_	Four-letter	92.9	13/14			odor	order
	Five-letter	64.3	9/14			ready	reacy
	Six-letter	21.4	3/14			region	resion
	Seven-letter	21.4	3/14			problem	promble
	Eight-letter	7.1	1/14			complete	coptime
Word frequency (collapsed across various subtests)			14.20	< 0.001			
•	HF	50.2	126/251				
	LF	33.7	87/258				

Frequency, grammatical class and concreteness (revised test) affected PB's performance, indicating that mild damage to the lexical system is a contributing factor to her spelling performance. However, phoneme-grapheme regularity did not affect her performance in spelling words, and she did not make phonologically plausible spelling errors (e.g. writing chare for chair). She made very few semantic errors (1.1%). Word length was a major determinant of performance and her errors in spelling words and non-words consisted almost entirely of neologisms (e.g. sleek \rightarrow sleeght; travel \rightarrow travi) resulting from letter substitutions, deletions, additions, and transpositions in the middle and end parts of the response. Her letters were consistently well formed. Her ability to spell words orally could not be tested extensively because of an independent deficit in naming letters. Thus, for example, when asked to spell wine, she traced all the letters correctly in the palm of her hand or on the table in front of her, but could not produce the name of the letter N; and for the word the, she spontaneously traced correctly all the letters in the palm of her hand, but was only able to name the letters H and the E. PB's difficulty in naming letters was a source of considerable frustration to her, and she refused to be tested further with this task. Nonetheless, the clear effect of word length on spelling performance and the types of spelling errors suggest a deficit at the level of the graphemic buffer.

of her spelling deficit was not influenced by the lexical status of the stimulus per se (see Fig. 2A, B and D). Furthermore, her spelling of non-words demonstrated that she was able to transcode phonological into graphemic information. Together with the fact that PB was able to repeat words and non-words correctly before, after and even during her spelling attempt, this patient strongly supports the view of the autonomy of phonological and orthographic representations. Although the patient's (sublexical) output phonology is intact and although her phoneme—grapheme conversion is mostly unimpaired, this does not help PB in improving her spelling behavior.

PB's spelling deficit cannot be attributed to auditory misperception or forgetting of the stimulus since she almost invariably repeated the words correctly orally after she spelled them [she only made four repetition errors in 947 trials (<1%), all of which were morphologically similar words], implying that her phonological buffer was intact—just as in the case of TH. Her spelling deficit cannot be attributed to a lack of knowledge of, or selective damage to, the end of words since she performed nearly flawlessly (97 and 94% correct for six- and eight-letter words, respectively) in a modified spelling-dictation task minimizing the involvement of working memory (see Fig. 3A and B). In this task, she was required to fill in the missing letter in a word. By calculating expected performances based on trigram frequen-

cies, PB performed far better than would be expected if she performed only using information based on trigram frequencies alone (six-letter word ABX yields an expected performance of 27.5% with X in the fifth position; six-letter word ABX yields an expected performance of 36.4% with X in the sixth position, and six-letter word AXB yields an expected performance of 42.6% with X in the fifth position; eight-letter word ABX yields an expected performance of 21.6% with X in the seventh position; eight-letter word ABX yields an expected performance of 42.3% with X in the eighth position, and eight-letter word AXB yields an expected performance of 41.3% with X in the seventh position). When a similar task was administered to TH in November 1999, he was correct on 82% of the trials (77/94 correct). Words were between seven and nine letters in length. Compared with his low proportion of correctly spelled words of the same length in writing-to-dictation (approximately 20-40% correct), this is a significant increase, although still not perfect. PB's good performance in this task was not merely due to a letter guessing strategy on the basis of the visual context provided by the word frame since she performed similarly well in letter probe tasks (93% correct for the last letter) in which she was asked to decide, on separate trials, whether a written letter was in the first two or last two positions of an aurally presented word (see Fig. 3C and D). This pattern of performance locates PB's deficit to the



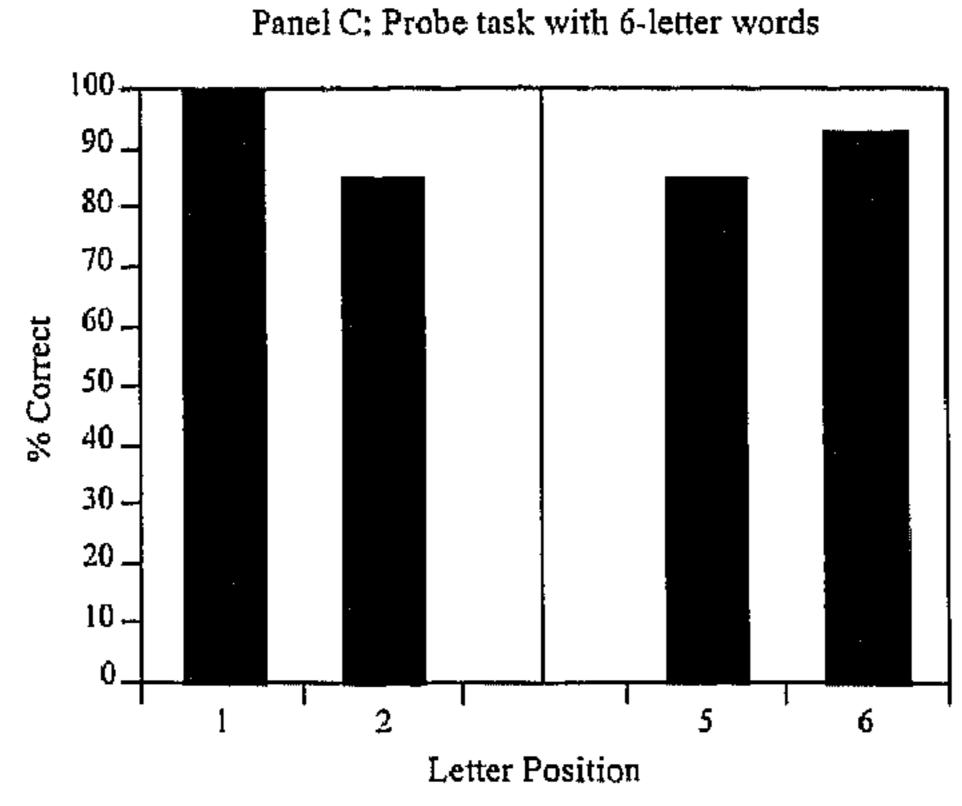


Fig. 3. Serial position performance for six- and eight-letter words in a modified writing-to-dictation task and for six-letter words in letter probe tasks. (A) and (B) The results on tasks in which PB had only to produce the single missing letter in six- and eight-letter words. PB performed very well on these two tasks, showing that she has normal access to the full spelling of words. The six-letter word completion task involved 618 trials (six tests with n = 103). The eight-letter word completion task involved 1040 trials (eight tests with n = 130). (C) PB's performance on two tasks in which she had to determine whether a letter of a word was within two positions of an aurally presented six-letter word. On one task, she was asked to determine whether the probed letter was contained within the first two positions of the word: positions 1 and 2. On the other task, she was asked to determine whether the probed letter was contained within the last two positions of the word: positions 5 and 6. All letter positions were probed on both tasks. Each position was probed 156 times: 104 positive trials and 52 negative trials. Overall correct performance for each position was determined by averaging correct positive responses and correct rejections across the two tasks.

nechanism that keeps graphemic representations active for urther processing.

Morphological boundaries

In contrast to TH, PB showed an effect of morphological composition in her spelling performance. For compounds such as nightstand, for instance, she made fewer errors on the first few letters of the second part of the compound (e.g. s and t) than on the last letters of the first part (e.g. h and t), even though the former occurred later in the word as a whole (see Fig. 4) (n = 54 for both the first and second words within the compound, where words 5–7 letters in length were normalized to five letter positions). Comparing performances for the last letter of the first word (57.4% correct) to performance on the first letter of the second word (79.6%) yielded a significant difference ($\chi^2 = 6.18$, P < 0.025).

Discussion

PB's error distribution in compound words indicates that she could control the placement of graphemic information in the buffer (i.e. spelling the compound as two separate words),

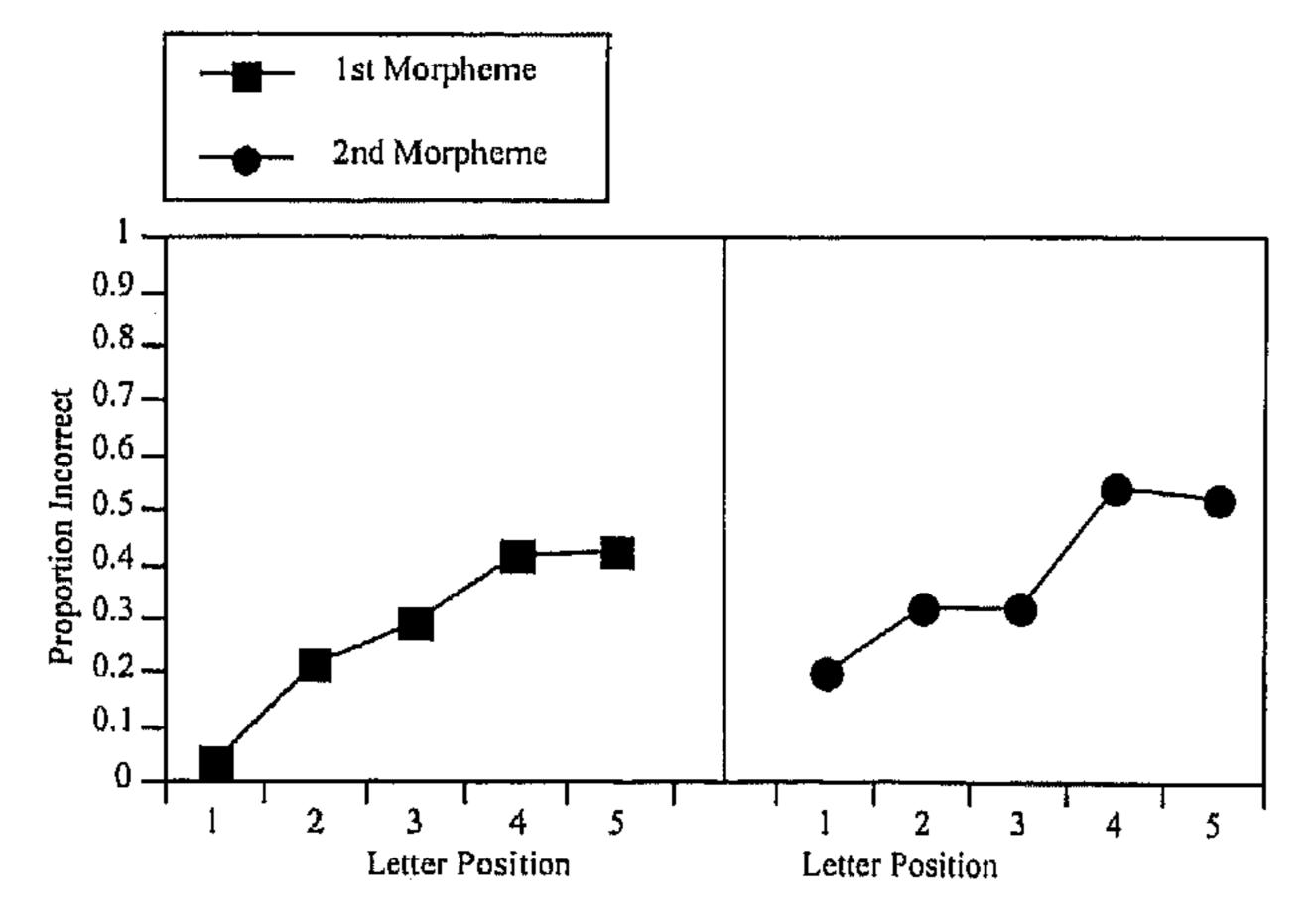


Fig. 4. Normalized serial position performance in spelling the two lexical morphemes in compound words. The serial position effect for compound words is strikingly different from the profile depicted in Fig. 2A, C and D. PB produced many fewer errors for the beginning letters of the second compound than the end letters of the first compound. Morpheme length of 5-7 letters was normalized to five letters for the 54 compound words included in the analysis ($\chi^2 = 6.18$, P < 0.025).

and the unit of control is the lexical morpheme. This is in contrast to TH, who did not show such an effect. Whether this effect is due to a strategy based on meta-linguistic

awareness (dividing words into their constituting morphemes and spelling one morpheme after the other) that some patients can use but others cannot, remains an open question.

General discussion

We have presented the cases of two dysgraphic patients, TH and PB, who showed a strong word-length effect in their spelling errors, making more errors on long than on short words. Furthermore, the probability of making a spelling error increased monotonically from the beginning to the end of words. Although both patients showed some small influences of lexical factors on spelling, their overall spelling performance satisfies the criteria given by Caramazza and therefore most closely resembles a deficit to a graphemic buffer, i.e. a working memory component that keeps graphemic information active for further output processing (Caramazza et al., 1987). The pattern of TH's and PB's errors suggests that the longer this information has to be stored in the graphemic buffer, the more likely it is to be lost.

TH and PB are very similar to BA (a patient studied by Ward and Romani, 1998), and to HR (a patient studied by Katz, 1991). All four patients show an increase in spelling errors from the beginning to the end of words. Like Katz, we interpret TH's and PB's serial position effect to be most likely due to a graphemic buffer deficit, although we cannot exclude damage to lexical orthographic representations. This deficit reflects an abnormally rapid decay rate such that letters at the end of the word are lost due to their position (i.e. items at the end require the most maintenance and would be most affected by an aberrant decay rate). Ward and Romani, however, presented an alternative interpretation for the linear increase in errors shown by their patient, BA. They argued that their patient suffered from incomplete activation of the abstract orthographic form and the incomplete activation had a greater impact on the ends of words than the beginnings of words. The main basis for Ward and Romani's preference for this interpretation over a graphemic buffer deficit was their patient's performance on a backward spelling task (i.e. the patient was given a word, chair, and had to spell it beginning with the last letter, riahc). BA did not show a linear increase in errors towards the 'end' of the word (e.g. riaXX), but instead made many errors on the last letter of the abstract word form (e.g. XXahc). Ward and Romani argued that if BA had a graphemic buffer deficit, she should have made more errors on the end of the string, regardless of the order of the letters as they appear in the abstract word form (Ward and Romani, 1998).

The main problem with this argument is the lack of understanding of how the backward spelling task is carried out. In order to spell backward, access to information from the graphemic buffer is required, but we can imagine at least two ways in which the task could be performed. The patient could generate a left–right representation (chair) and then scan right–left to spell the word backwards. Or, the patient could access the information by working repeatedly towards

the end (ch, cha, chai, chair). In the latter case, no improvement would be expected on the end of the word since the spelling task would ultimately be the same as spelling in a forward direction. Thus, no improvement in performance on the ends of words when spelling backwards does not necessarily localize the deficit, since we can imagine at least two ways in which a patient could perform the task. Moreover, BA's performance did not differ when spelling non-words, which suggests that she was retaining the representation of the segmental structure to be produced in the left-right fashion and working towards the end of the item to be produced. The lack of understanding of how a backward spelling task is completed, and thus the uncertainty about what performance on this task is revealing about the underlying deficit, lead us to question the interpretation presented by Ward and Romani regarding their patient's deficit (Ward and Romani, 1998).

TH's and PB's deficits fit most clearly the pattern established as a graphemic buffer deficit, with one main difference. Although all of the reported patients presumably have a deficit at the level of the graphemic buffer and little or no damage to abstract orthographic representations, the error patterns differ. TH's and PB's error pattern (linear increase), as well as the error patterns for HR and BA, contrast dramatically with the pattern reported for other 'graphemic buffer patients' (bow-shaped function; e.g. Caramazza and Miceli, 1990; Jónsdóttir et al., 1996). It may be that the different error patterns represent different types of damage of a broader disorder to what has been called the 'graphemic buffer'. Patients who exhibit a bow-shaped function in the error pattern are exhibiting a normal but exacerbated pattern of performance (see Wing and Baddeley, 1980 for analysis of normal error patterns in spelling). Thus, these patients may suffer from a reduced level of activation in the lexical system that results in many spelling errors. This reduced lexical activation level decreases performance overall, but does not interfere with the normal workings of the graphemic buffer. In contrast, patients who show a linear increase in errors towards the ends of words may have a decay deficit that affects the graphemic buffer in such a way as to alter the actual functioning of this working memory system. These error patterns do not resemble error patterns found with normal spellers and seem to reflect an abnormally rapid decay of information such that information at the end of words is lost.

Recently, Houghton and colleagues (Houghton, 1990; Houghton et al., 1994; Shallice et al., 1995) proposed a spelling model that works without postulating a (graphemic) buffer. This so-called 'competitive queuing' model is a connectionist model that comprises three layers of nodes: one layer of control nodes, one layer of nodes representing the letters and one layer that functions as a 'competitive filter'. The letter nodes are activated by weighted connections from a pair of control nodes whose activation pattern varies with time. This pair of nodes consists of an initiate (I) node and an end (E) node. Each letter node has weighted

connections to both the I- and the E-nodes. Letter nodes with strong connections to the I-node will receive most activation at the beginning of the word (e.g. the initial letters) and those with strong E-node connections (e.g. the final letters) will receive most input towards the end of the word. The competitive filter identifies the most highly activated letter node at any given time, selects the corresponding filter node and inhibits the rest. The selected filter node then feeds inhibition back to the letter node, resulting in suppression of the node that was just selected previously.

At the beginning of the spelling process, only the I-node is active (and the E-node is inactive). As time passes, the I-node's activation decays while the activation of the E-node increases. This time-varying activation pattern allows different letters in the sequence to become maximally active at different times. For the spelling of double (or geminate) letters, the model requires a special mechanism implemented by a 'geminate feature node'. Spelling of repeated letters, such as the 'a' in damage, does not pose a problem to the model. Even after selection and suppression of the first 'a', the letter 'a' can be activated and selected again due to connections to the E-node, which enables previously activated and suppressed letters to become activated again.

Could the competitive queuing model be used to account for the patient data we presented in this study? Shallice damaged a competitive queuing model in such a way as to simulate the bow-shaped error distribution exhibited by graphemic buffer patients like LB and AS (Shallice et al., 1995). However, our patients show a markedly different error pattern. Nevertheless, it might be conceivable that selective damage to the E-node would result in a linear serial position effect of errors as exhibited by TH, PB and BA. This is because the activation of letters will decrease linearly over the word because the strength of the weights from the I-node to the letter node layer gradually decreases. However, as pointed out by Ward and Romani (1998), lesioning of the E-nodes leads to the prediction of a particular spelling problem with repeated letters. To test whether this prediction could be supported by TH's data, we looked at his spelling performance in the 'word length' sublist of the JHU Dysgraphia Battery. Excluding those words that had double letters or geminates, TH made eight errors on words including repeated letters and spelled 11 repeated letter words correct. The same was true for patient BA (Ward and Romani, 1998): BA was no worse at writing words with repeated letters than words with no repeated letters. On the JHU Dysgraphia Battery's double-letter list, PB scored 48/98 (49.0%) correctly for words without a double letter and 53/95 (55.8%) correctly for words with a double letter, but this difference was not significant ($\chi^2 = 0.89$, P > 0.10). Thus, although selective damage to the E-node in a competitive queuing model could account for the linear increase in errors of patients like TH and PB, performance on repeated letters is not consistent with this hypothesis. Furthermore, Ward et al. (1998) recently showed that damage to both the I- and the E-node could reproduce the spelling pattern of

patient BA and yielded similar effects as selective damage to the E-node alone.

The fact that TH and PB seem to suffer from a rapid decay

of information in their graphemic buffer raises the issue of why patients do not refresh information in the graphemic buffer using phonological information. In fact, Jónsdóttir et al. (1996) claimed that intact phonological processing can help keep the orthographic representations active while the patient is engaging in the sequential output process of spelling. The authors offered this as an explanation as to why their graphemic buffer patient's overall performance level was much lower than another graphemic buffer patient's, LB, presented by Caramazza and colleagues (Caramazza et al., 1987; Caramazza and Miceli, 1990). The patients reported here, TH and PB, flawlessly repeated quite long words before and after they wrote them down, indicating no damage to their phonological buffer. However, although their phonological buffer was unimpaired, they showed severely impaired spelling behavior, suggesting that the good phonological information does not necessarily lead to improved spelling performance, as Jónsdóttir et al. have argued. But why would TH and PB not use this information if it were available? If TH and PB used lexical information to refresh information in the graphemic buffer, it could be done on a whole-word basis, rather than segmentally, and would not provide additional information to help them retain the final letters of words. In addition, TH's non-word spelling was quite poor, suggesting a fairly restricted ability to transcode phonological information into graphemic information. Thus, refreshing information in the graphemic buffer sublexically, which could be done segmentally, was not an option for TH. Therefore, regardless of how well he could retain phonological information, as demonstrated by his repetition of the target word after he attempted to spell it, TH could not use this information to improve his spelling performance. For PB, however, this was not the case. She could spell nonwords to some degree, indicating the (limited) ability to transcode phonological into graphemic information. Nevertheless, her error pattern was similar to TH's. In our view, this demonstrates that phonological and orthographic representations are autonomous (for further evidence with regard to the autonomy of orthographic representations, see Rapp et al., 1999).

A final contrast in performance between TH and another graphemic buffer patient (LB), who shows a bow-shaped error function, may provide additional information regarding the nature of the difference to the graphemic buffer. When TH was asked to read a list of short versus long words, he performed at a very high level (99% correct, 196/198). In contrast, LB's deficit to the graphemic buffer impaired his reading (Caramazza et al., 1996), and LB's bow-shaped error distribution was different from TH's monotonically increasing curve. We hypothesized that TH suffers from an abnormally rapid decay of information in the graphemic buffer, whereas LB suffers from a reduced level of activation in the lexical system. Since reading is carried out in parallel (i.e. there is

no scanning required), the temporal decay of information is not fast enough to have an effect on TH's reading performance. That is, the rapid decay of information hypothesis states that for output processes that occur very fast and in parallel, a graphemic buffer deficit will not show any effect, whereas in output processes that are slower and have to be carried out sequentially, an increasing distribution of the errors will be visible. PB was also only mildly impaired in reading, providing additional evidence that a graphemic buffer deficit resulting from rapid decay of information does not affect output processes that occur in parallel, such as reading. Bow-shaped error distributions are presumably the result of a different underlying cause (see discussions above), and this cause also manifests itself in fast output processes like reading aloud. Recently, Hanley and Kay (1998) reported the case of a graphemic buffer patient, JH, who performed fine at reading words and non-words. Unfortunately, however, they do not report the distribution pattern (bow-shaped or monotonically increasing) found in JH's spelling errors. Future research on 'graphemic buffer patients' should focus on the underlying causes that are responsible for the different error distributions.

Conclusion

In the cognitive and the neural sciences, a fundamental distinction is drawn between the mechanisms that compute mental representations and the working memory systems or buffers that temporarily hold those representations for further processing. This distinction is supported by behavioral studies with neurologically intact and brain-damaged subjects and neuroimaging studies with human subjects. There is also evidence for the finer-grained distinction between phonological and graphemic buffers that are used, respectively, in speaking and in spelling. Here we show that the mechanism for keeping active abstract letter forms (graphemes) for spelling can be damaged independently of other aspects of the spelling process, and that the graphemic buffer functions autonomously of its phonological counterpart. The patients presented in this paper, TH and PB, suffer (mainly) from a spelling impairment, where their spelling errors increase monotonically towards the end of a word, much like patients reported by: (Katz, 1991: HR; Ward and Romani, 1998: BA), in contrast to patients reported by: (Caramazza et al., 1987: LB; Jónsdóttir et al., 1996: AS). We have argued that two types of impairments might affect the graphemic buffer: one in which information decays abnormally rapidly (TH, PB, BA and HR), resulting in errors increasing linearly towards the end of words, and the other in which noise in the system depresses the normal pattern (LB and AS), resulting in a bow-shaped error function. Both PB and TH correctly spell to dictation only the first few letters of words, despite showing normal ability to repeat the words orally and to access their full spelling in tasks that minimize the involvement of working memory. This pattern of performance locates their deficit to the mechanism that keeps graphemic representations active for further processing, and shows that the functioning of this mechanism is not controlled or 'refreshed' by phonological (or articulatory) processes.

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Serial order effects in spelling errors: evidence from two dysgraphic patients

N. O. Schiller, J. A. Greenhall, J. R. Shelton and A. Caramazza

Abstract

This study reports data from two dysgraphic patients, TH and PB, whose errors in spelling most often occurred in the final part of words. The probability of making an error increased monotonically towards the end of words. Long words were affected more than short words, and performance was similar across different output modalities (writing, typing and oral spelling). This error performance was found despite the fact that both patients showed normal ability to repeat the same words orally and to access their full spelling in tasks that minimized the involvement of working memory. This pattern of performance locates their deficit to the mechanism that keeps graphemic representations active for further processing, and shows that the functioning of this mechanism is not controlled or 'refreshed' by phonological (or articulatory) processes. Although the overall performance pattern is most consistent with a deficit to the graphemic buffer, the strong tendency for errors to occur at the ends of words is unlike many classic 'graphemic buffer patients' whose errors predominantly occur at word-medial positions. The contrasting patterns are discussed in terms of different types of impairment to the graphemic buffer.

Journal

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Primary diagnosis of interest

Left hemisphere stroke

Author's designation of case

TH PB

Key theoretical issue

• Dysgraphia, effects of serial order

Key words: neuropsychology; dysgraphia; serial order effects in spelling; graphemic buffer disorder

Scan, EEG and related measures

CT scan, vascular MRI scan

Standardized assessment

The Johns Hopkins University Dysgraphia Battery, the Philadelphia Naming Test

Other assessment

Self-contained spelling tests

Lesion location

- TH: infarct in the territory of the left middle cerebral artery
- PB: superior/parietal left middle cerebral artery territory infarction

Lesion type

TH: left hemisphere stroke PB: subarachnoid haemorrhage

Language

English