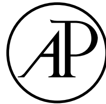

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Preserved orthographic length and transitional probabilities in written spelling in a case of acquired dysgraphia☆

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Abstract

We present the performance of a patient with acquired dysgraphia, DS, who has intact oral spelling (100% correct) but severely impaired written spelling (7% correct). Her errors consisted entirely of well-formed letter substitutions. This striking dissociation is further characterized by consistent preservation of orthographic, as opposed to phonological, length in her written output. This pattern of performance indicates that DS has intact graphemic representations, and that her errors are due to a deficit in letter shape assignment. We further interpret the occurrence of a small percentage of lexical errors in her written responses and a significant effect of letter frequencies and transitional probabilities on the pattern of letter substitutions as the result of a repair mechanism that locally constrains DS' written output. © 2002 Elsevier Science (USA). All rights reserved.

1. Introduction

Any theory of written spelling must address the question of how graphemic knowledge—the knowledge which allows us to know that, for example, the word /tʃɛir/ is graphically represented by the string of orthographic symbols CHAIR—is translated into a motor sequence that enables one's hand to correctly write the letters in the word CHAIR. While the exact architecture of the spelling system remains in

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question, there are several structural elements that are generally agreed upon. A basic overview of this model is presented in Fig. 1.

Briefly, regardless of the nature of the item to be spelled (word or nonword, orally or visually presented), the input converges at a temporary buffer stage (the graphemic buffer) where it is held as a string of letter representations during its conversion to the appropriate output modality (Caramazza, Miceli, Villa, & Romani, 1987; Ellis, 1988; Margolin, 1984; Rapp & Caramazza, 1997; but see Lesser, 1990, for a different proposal). For written spelling, these conversion processes include the transformation of individual graphemes into letter shapes and the motor processes required to produce them; for oral spelling, graphemes are turned into letter names and the appropriate articulatory processes are activated.

The role of the graphemic buffer is to keep the orthographic strings generated by the lexical and/or sublexical spelling processes active while more peripheral, sequential processes are taking place, allowing for ordered execution of the letters in either oral or written spelling. The information held in the graphemic buffer is assumed to be an amodal string of graphemes. By amodal here we mean that such representations do not consist of letter names or letter shapes, but rather of symbolic representations of letter identities.

This description of the graphemic buffer provides for specific predictions regarding the nature of the deficits resulting from damage to this level (Caramazza et al., 1987). Due to its position at the interface between input and output processes, damage to the graphemic buffer not only should affect both written and oral spelling but should also result in a pattern of errors that should remain constant across output modality. These spelling errors should not be sensitive to lexical effects, and should reflect working memory impairments. Patients with deficits of this nature have indeed been reported (e.g., Caramazza et al., 1987; Jónsdóttir, Shallice, & Wise, 1996; Katz, 1991; Kay & Harley, 1994; McCloskey, Badecker, Goodman-Schulman,

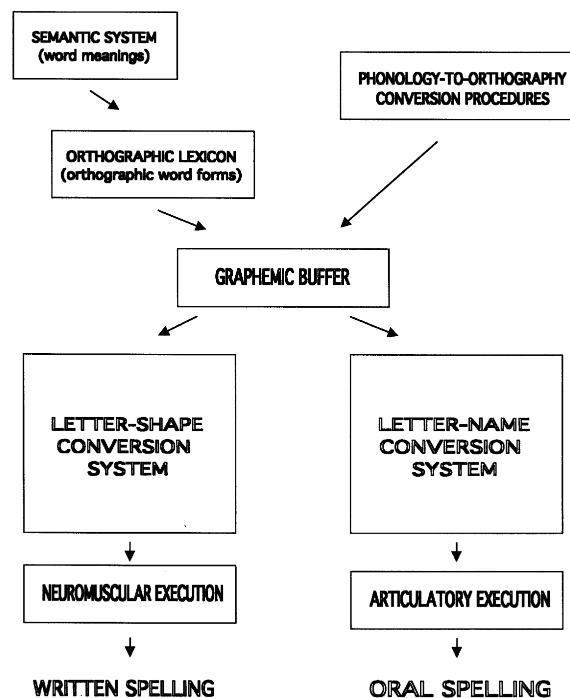

Fig. 1. A model of spelling.

& Aliminosa, 1994). Moreover, patients' error patterns have revealed that the graphemic representations held in the buffer have multidimensional structures containing information such as the identity, order, and consonant/vowel status of each grapheme (Caramazza & Miceli, 1990; McCloskey et al., 1994; Ward & Romani, 2000; see Tainturier & Rapp, 2001, for review). These features are encoded in such a way that each can be selectively preserved or destroyed. For example, Ward and Romani (2000) recently described BA, whose substitution errors consistently preserve the consonant–vowel (C/V) status of each letter (see also Caramazza & Miceli, 1990; Cubelli, 1991; Jónsdóttir et al., 1996; McCloskey et al., 1994). Other research indicates that geminates may have a special status, with doubling encoded independently of position and/or grapheme identity (Caramazza & Miceli, 1990; McCloskey et al., 1994; Miceli, Benvegnù, Capasso, & Caramazza, 1995; Tainturier & Caramazza, 1996).

If damage is sustained to a postbuffer mechanism, the pattern of spelling errors assumes a different profile. Postgraphemic buffer processing involves modality-specific mechanisms for oral and written spelling, rendering performance in each modality independent from the other. Patients with impaired written production and preserved oral spelling have been reported in the literature. Kinsbourne and Rosenfield (1974) reported the case of CM, who was 100% correct in oral spelling but only 53% correct when writing the same words to dictation. Goodman and Caramazza (1986) presented patient MW, who produced phonologically implausible errors only in written spelling, his error rate unaffected by grammatical class or word length. Examples of the complementary pattern exist as well. In 1965, Kinsbourne and Warrington reported patient JP, who was 93% correct on written spelling tasks, but only 7% correct on oral spelling tasks. Bub and Kertesz' (1982) patient JC was greatly impaired in oral spelling, writing words such as TELEPHONE and HAMMER correctly but remaining unable to say the letters of words such as CAT and POND. Within these broad classifications, however, spelling performance can be examined further with respect to the specific processes employed to produce the appropriate output. Given that the errors of the patient we present here were confined to written spelling, we will focus our discussion on this modality.

While the exact nature of the postbuffer processes for written spelling remains unresolved, it is clear that there exist, at some level(s), letter-form representations that encode the shape, case, and style of the grapheme to be produced (Ellis, 1988; Margolin, 1984; Rapp & Caramazza, 1997). Each member of the amodal string in the graphemic buffer must first be transformed into the appropriate allograph, an entity specifying the letter shape as well as its case and style (cursive or print). We refer to these processes as allographic (or letter-shape) conversion. The graphic motor pattern of this allograph is then activated, designating the direction, size, position, and order of the strokes to be executed. Finally, this sequence is translated into neuromuscular execution, determining the absolute letter size and writing speed.

Patients with allographic conversion impairments produce writing that is composed of well-formed letters, but have problems selecting the appropriate letter, case, and/or style to be rendered (e.g., De Bastiani & Barry, 1989; Hanley & Peters, 2001; Rothi & Heilman, 1981). Hanley and Peters (2001) found that their patient (GG) produced substitution errors with the substituted letter often highly visually similar to the target (23 of the 37 substitutions had high spatial similarity to the target). For example, he wrote E for C and N for V.[1] In addition he displayed a disregard for case, writing words in mixed case (e.g., LEg, DiD) and producing the

[1] Note however that visuo-spatial and motoric similarities are often difficult to disambiguate, and the existing literature is rather impoverished in this regard. We will therefore not purse this distinction further.

inappropriate version of a requested letter. Case substitution also occurred when copying upper- and lowercase letters. De Bastiani and Barry (1989) document an Italian patient who appeared to be unable to control the case of his responses, writing words in mixed case 54% of the time. His errors, such as "solve" (he solves) > SorVe (a nonword) and "latte" (milk) > LAtte, were well-formed, unambiguous letter and case substitutions. Patients with an allographic deficit may also show a selective impairment for writing in either upper- or lowercase. Patterson and Wing (1989) report on DK, who was significantly more impaired in producing lowercase letters, rendering him incapable of transcribing words from upper- to lowercase (he was 92% accurate when transcribing in the reverse direction; see also Hanley & Peters, 1996).

More peripheral damage leads to motor errors in the stroke pattern, resulting in an ill-formed product (e.g., De Bastiani & Barry, 1989; Friedman & Alexander, 1989; Kinsbourne & Rosenfield, 1974; Margolin & Binder, 1984; Rothi & Heilman, 1981). The direction, size, position, and order of each stroke must all be specified by the graphic motor pattern (Ellis, 1988); loss of information in any of these areas could lead to incomprehensible output. Baxter and Warrington (1986) reported a patient (IDT) who could copy letters, but when asked to write them on his own produced illegible scrawls, thus suggesting that the ability to execute the motions necessary for writing may dissociate from the ability to employ these same motor skills in written spelling. Finally, disorders of neuromuscular execution may affect specific muscles in the mechanics of writing and alter the speed and size of letter execution (e.g., the well-formed, micrographic letters executed extremely slowly by Parkinson's patients; see Ellis, 1988; Margolin, 1984).

Some authors have also hypothesized that visual, kinaesthetic, and/or attentional feedback plays a role in guiding stroke sequence. Ellis, Young, and Flude (1987) proposed that the frequent omission or repetition of strokes and letters observed in their patient VB was due to her inability to use visual and kinaesthetic feedback. VB was especially prone to these errors when there was a series of similar (or identical) strokes or letters, writing KFFN instead of KEEN or LADDDER instead of LADDER. Conversely, Kinsbourne and Warrington (1965) reported that JP's oral spelling improved from 7% correct to 33% correct when he was allowed to perform writing movements, apparently gaining useful information from the kinaesthetic feedback.[2]

In this article we present an analysis of the impaired writing performance of a patient, DS, who produced well-formed letter substitution errors in written spelling—when presented with a picture of a mushroom she wrote HEgRKAAR, while saying aloud "mushroom," and when presented with a picture of a cake she wrote ICUL while spelling aloud "C-A-K-E." She had no peripheral deficits except for reduced visual acuity due to bilateral cataracts. On a series of written and oral spelling tasks, DS' performance demonstrated a striking dissociation between oral (95% correct) and written (10% correct) spelling. More importantly, virtually all DS' written spelling responses were characterized by letter substitutions and respected the orthographic rather than the phonological length of the target word. DS' performance is not accounted for by a motor disorder, as letters were executed fluently, using her dominant hand, and were all well-formed. In the study presented below we will analyze the nature of the graphemic information that is retained in her responses. The stark contrast between DS' written and spoken spelling indicates that her

[2] Cubelli and Lupi (1999), however, have postulated an updating operation specific for handwriting that can be impaired separately from visual, kinaesthetic, or attentional mechanisms.

graphemic buffer is intact; her well-formed letter substitutions and case mixing implicate damage to allographic conversion processes.

2. Case history

At the time of testing, DS was a 52-year-old left-handed Caucasian woman with bilateral below-the-knee amputations and a history of insulin-dependent diabetes and hypertension. DS suffered a left-hemisphere infarct in January 1998. Following CT scanning, it appeared that the infarct involved the area of the posterior central artery affecting the left mediotemporal and occipital lobes, with minimum edema and no midline shift. An old infarct was also located in the left occipital region, as well as dense calcifications of the vertebral and carotid arteries (see Fig. 2). Following the last infarction she was reported to have a right visual field cut, right hemiparesis, and

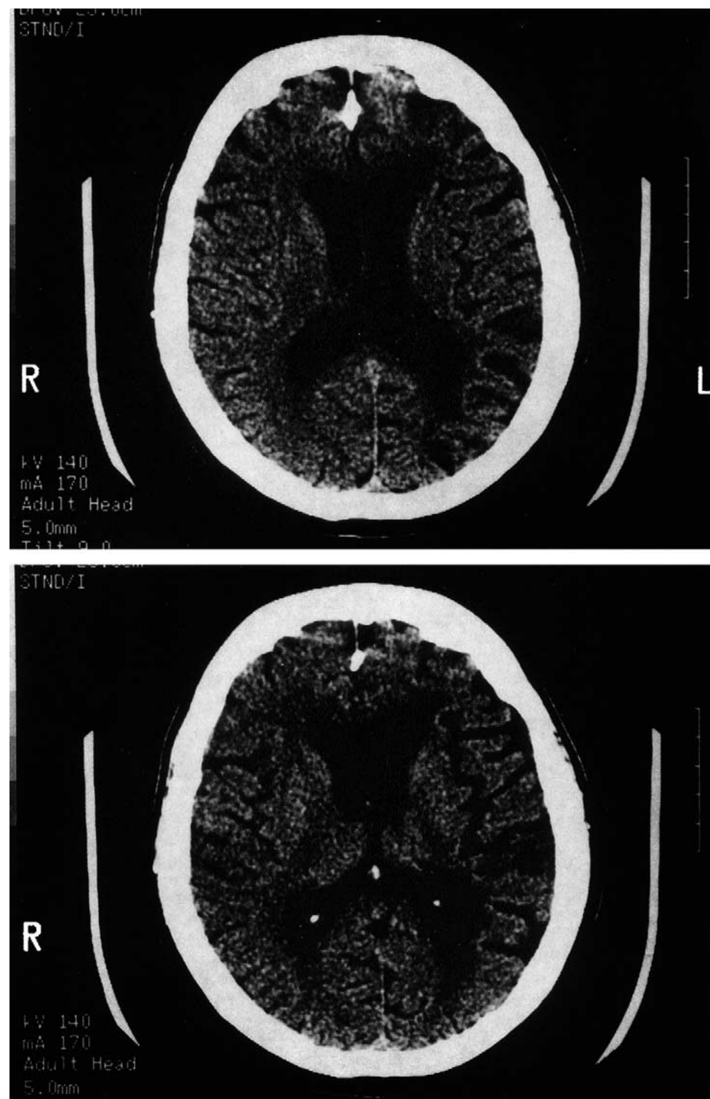

Fig. 2. Scans.

word-finding difficulties. After her stroke DS remained hospitalized until her death secondary to renal failure in January 1999. DS was college-educated, and her professional history included working as a secretary at a major medical center. The data reported here were collected between March 1998 and January 1999.

DS was initially administered a series of screening tests (Cognitive Neuropsychology Laboratory Screening Battery, unpublished). Comprehension of words and sentences was minimally impaired in the auditory modality (94% correct) but only slightly above chance in the written modality (60% correct). Errors involved selection of a semantically related foil (e.g., money > wealth). On a spoken word–picture matching comprehension task (constructed using the Snodgrass & Vanderwart set (1980); see Hillis & Caramazza, 1995), where she was presented on different occasions a picture with either the correct name, a semantically related name (e.g., a picture of a pear and the word apple), or a formally related name (e.g., a picture of a pear and the word bear), her performance was 89% correct overall (83% for the matching condition, 99% for the formal condition, and 83% for the semantic condition). Repetition performance was accurate for both sentences (99% correct) and words (93% correct), but mildly reduced for nonwords (80% correct). Her spontaneous speech was fluent and grammatical, with hesitations for word finding. Similar performance was obtained on a picture description task (Cookie Theft). Picture naming to confrontation was characterized by semantic errors, circumlocutions, and no responses for both objects (20% correct) and actions (0% correct). Naming to definition was 30% correct. Word fluency was reduced with six animal names produced in a minute and 10 words beginning with the letter "F" produced in a minute. Reading performance was severely impaired with no correct response for either word or nonword stimuli. Her attempts were laborious and bore little resemblance to the target (e.g., she read "want" as "thin," and "became" as "e-t-h-a-e-f, it doesn't make sense"). Sentence reading could not be tested. Oral spelling to dictation was 95% correct for words, and 50% correct for nonwords. On oral spelling of pictures she correctly spelled what she named, but her naming responses contained semantic errors. In contrast, written spelling to dictation and to picture was on average 3% correct. Recognition of words spelled aloud by the examiner was 81% correct.

3. Spelling performance

Item variability effects. To ensure that DS' dissociation between oral and written spelling could not be accounted for in terms of item variability, we selected a subset of the Snodgrass and Vanderwart stimuli (1980), which had been administered on different occasions for writing and spelling. DS' performance in writing to dictation and oral spelling for the same items was 7 and 100% correct, respectively (see Table 1). Her oral spelling performance did not change when a larger set of words was administered (100% (181/181) correct). The vast majority of DS' writing errors were nonword responses (93%; e.g., cake > ICUL) with rare lexical responses (7%; e.g., harp > FOUR).

Table 1
DS' performance across tasks

Task	% correct	No. correct
Writing to dictation (List 1)	7	2/31
Oral spelling to dictation (List 1)	100	31/31
Writing to dictation (List 2)	4	4/107
Recognition of spelled words (List 2)	75	80/107

Frequency and orthographic regularity effects. To determine whether lexical factors such as word frequency and orthographic regularity affected DS' performance in written spelling, she was dictated a set of 107 words which varied in frequency and regularity (from the Cognitive Neuropsychology Dyslexia Battery, unpublished). She was 4% correct. Her errors were either nonword responses (66%; e.g., budge > EKELE) or lexically unrelated responses (34%; e.g., love > CENT). There were no effects of frequency (with low- and high-frequency words 2 and 6% correct, respectively) nor of regularity (with low- and high-probability words 5 and 0% correct, respectively). The same list of words was also administered for recognition. DS was 75% correct in recognizing the words spelled aloud by the examiner (see Table 1). Her errors in recognition were nonresponses (10/27 errors), lexical misidentifications (12/27, e.g., dance > dancer; cheer > cheese), fragments (2/27), and nonword responses (3/27; e.g., sketch > skentch, urge > U-D-G-H). Relative to the previously

Target	Response	Handwritten Response
mouse	foutn	
record player	TEKORJ PARTER	
deer	ELiS	
asparagus	ASTANOTHE	
barn	FASH	
duck	FiCH	
needle	FARRES	
cigarette	SEROUCHE	
rooster	FOSHER	
sled	STEK	
tennis racket	FANiA PLOWN	
ostrich	SHOUMOJN	
harp	FOUR	
artichoke	ASOUgHOKF	
sailboat	SHEN Coug	
window	WiDWoK	
bell	BELL	
knife	SUREG	
anchor	SMRUgT	
butterfly	FLaugHERES	
cake	ICUL	

Fig. 3. Examples of DS' handwriting.

administered aural recognition, this list contained numerous abstract and longer words, factors which induce below ceiling performance in normal subjects. DS' error pattern shows regularity and frequency effects, with low-frequency/low-probability words identified correctly less the least often (with low-frequency/low-probability words 58% correct; low-frequency/high-probability words 86% correct; high-frequency/low-probability words 79% correct; and high-frequency/high-probability words 87% correct).

On both writing to dictation tasks her letter execution was fluent, accurate, and without stroke errors (see Fig. 3). These results confirm the striking dissociation observed between DS' oral (100% correct) and written (ranging from 1 to 7% correct) spelling abilities. Her spelling deficit is independent of input modality, and is not affected by lexical factors such as frequency or orthographic regularity. Her written responses seem to faithfully retain the graphemic length of the input. Most of the responses are nonlexical errors which bear little resemblance to the target. To further investigate the properties of her errors, DS was asked to write additional items to dictation.

4. Written spelling of single words

To carry out an error analysis to assess the locus of her spelling deficit, we asked DS to spell 210 words. To ensure correct understanding of the input stimulus she was asked to repeat the word before writing it. For the few items she misperceived, she was given the stimulus again until she correctly repeated it. Her written responses were produced effortlessly, and she often identified them as incorrect, but was unable to produce a better response. She produced a total of 12 correct responses (6% correct). Her errors could be classified as lexical (25% (49/198); e.g., dog > RUG) or nonlexical responses (75% (149/198); e.g., artichoke > ASOUgHOKF) (see Table 2). Lexical and nonlexical responses were analyzed separately.

Length effect. Errors were first analyzed in terms of their length to see whether DS' responses were closer in length to the graphemic or the phonemic representation of the input. We therefore selected all input stimuli which had a different length when measured in graphemic and in phonological units (e.g., $\langle \text{LIGHTS} \rangle_{L=6}$ vs $/\text{l}\underline{\text{aI}}\text{ts}/_{L=4}$). There were 34 such stimuli to which a lexical response was produced, and 116 to which a nonlexical response was produced. The respective graphemic and phonological lengths of these items were compared with the graphemic length of DS' responses. DS' lexical responses had the same length as the graphemic representation of the stimuli on 91% (31/34) of the cases and the phonological representation of the stimuli on 6% (2/34) of the cases (1 response was shorter than either the phonological or the orthographic representation). DS' nonlexical responses had the same length as the graphemic representation of the stimuli on 85% (98/116) of the cases and the phonological representation of the stimuli on 4% (4/116) of the cases (14 responses

Table 2
DS' written spelling performance

Overall performance	% (no.) correct
Written spelling	6.0 (12/210)
Error breakdown	% (no.) error
Lexical errors	25 (49/198)
Nonlexical errors	75 (149/198)

Table 3
DS' error breakdown (% and (no.) error) for lexical and nonlexical responses for stimuli with different graphemic and phonological lengths

Response length	Error type		Total errors
	Lexical	Nonlexical	
Equals input graphemic length	91 (31/34)	85 (98/116)	86 (129/150)
Equals input phonological length	6 (2/34)	4 (4/116)	4 (6/150)
Different[a]	3 (1/34)	12 (14/116)	10 (15/150)

[a] Approximately half of these responses were shorter, and half longer than both input lengths.

were either shorter or longer than either the phonological or the orthographic representation; see Table 3). Lexical responses yielded a total of 3 deletion and 34 substitution errors, and nonlexical responses a total of 7 deletion, 1 insertion, and 58 substitution errors. Collapsing across lexical and nonlexical responses, DS' responses corresponded in length to the orthographic representation of the input on 86% of the cases (129/150) and to the phonological representation on only 4% of the cases (6/150).

One preliminary conclusion can be drawn. DS' perfect oral spelling indicates that she has access to intact graphemic representations of the words to be spelled. Consistent with the intact access to graphemic representations is the finding of preserved length in terms of number of letters.

To further assess which properties of the graphemic structure remained unaffected or partially preserved, a series of post hoc analyses of the errors were carried out, separately for lexical and nonlexical responses. DS' performance on single-letter processing tasks was also assessed. Errors were analyzed in terms of (1) error rate by stimulus length, (2) error rate by grapheme position in the word, (3) consonant–vowel structure, (4) geminate–singleton grapheme status, and (5) case mixing.

Error rate by stimulus length. The distribution of DS' lexical and nonlexical errors by stimulus length is reported in Table 4. As shown, errors affect stimuli of all lengths at approximately equal rates. This, however, may represent a floor effect. Also, lexical errors tend to occur for shorter stimuli (up to five letters long), whereas nonlexical errors are more evenly distributed across all lengths.

Error rate by grapheme position in the word. Because substitution errors constituted DS' main error type and because these errors are the least ambiguous in terms of analyses of error by position, this analysis includes only substitution errors. DS' substitution errors were scored in terms of error by position, assigning a value of 1 to each substituted letter (e.g., "nut > KEG" would receive a score of 1 on each letter position). As Table 5 exemplifies, DS' error rate across letter positions follows a flat curve (error rates for lexical and nonlexical responses did not differ, so the results were collapsed).

Table 4
DS' percentage (number) of errors by error type and stimulus length (in graphemes) for all error types (substitutions, deletions, insertions)

Stimulus		Error type		Total errors
Length	*N* stimuli	Lexical errors	Nonlexical errors	
<4	13	40 (4)	60 (6)	77 (10)
4	73	44 (30)	56 (38)	93 (68)
5	68	21 (14)	79 (54)	100 (68)
6	19	5 (1)	95 (18)	100 (19)
>6	37	6 (2)	94 (34)	97 (36)

Table 5
Distribution of DS' substitution errors by grapheme position for four- and five-letter-long stimuli

Length	N	% error by position				
		1	2	3	4	5
4	62	81	73	82	86	
5	59	80	75	80	93	93

Table 6
DS' error rates for consonants and vowels (substitution errors only)

a. Percentage and number of consonants and vowels in the corpus, and in DS' responses, and which were subject to an error

Letter type	% (no.) corpus	% (no.) errors
Consonant	62 (556/899)	65 (468/723)
Vowel	38 (343/899)	35 (255/723)

b. Percentage (and number) of errors on consonants and vowels for lexical versus nonlexical responses

Letter type	Lexical errors	Nonlexical errors
Consonant	80 (104/130)	86 (364/426)
Vowel	72 (54/75)	75 (201/268)

Consonant–vowel structure. Studies of patients with graphemic buffer deficits have provided evidence indicating that consonants or vowels may be selectively impaired, and that spelling errors preserve C/V status (e.g., Caramazza & Miceli, 1990; Jónsdóttir et al., 1996; McCloskey et al., 1994). Rapp and Caramazza (1997) have shown that such information may not be preserved in patients with postbuffer deficits. To assess whether consonants and vowels are selectively impaired and whether C/V status is preserved in DS' spelling errors, we calculated the number and distribution of consonants and vowels in the corpus and the rate at which consonants and vowels were subject to an error.

Table 6a shows that DS makes more errors on consonants (65%) than on vowels (35%). In order to assess whether this is a significant difference, we need to calculate the error rate for consonants and vowels expected by chance as, presumably, consonants and vowels are not equally distributed in the orthography. In order to estimate the proportion of consonants and vowels in actual usage in the orthography, we counted the total number of consonants and vowels in the corpus of words administered to DS. We found that consonants made up 62% (556/899) of the letters, and vowels the remaining 38% (343/899).[3] Using these values to calculate expected values, we found that DS' error rates for consonants and vowels did not differ from that expected by chance (consonants: $\chi^2(1) = 0.89$, NS; vowels: $\chi^2(1) = 1.5$, NS). Thus, DS produces a similar number of errors on consonants and on vowels as would be expected from their distribution in the orthography. There is no difference in the distribution of these errors for lexical versus nonlexical errors (see Table 6b).

Table 7a shows that of the 723 single letter substitutions, consonants were substituted for consonants on 77% (358/468) of occasions and vowels were substituted for vowels on 39% (99/255) of occasions. Thus, C/V status was preserved in 63% (457/723) of the substitutions. To calculate whether DS' C/V status preservation

[3] Using the same procedure, Ward and Romani (2000) estimated that consonants made up 60.3% of letters in their corpus, and vowels the remaining 39.7%, and Baddeley, Conrad, and Thomson (1960) estimated that consonants made up 61.7% of letters in their corpus, and vowels the remaining 38.3%. The impressive similarity of these results indicates the reliability of these measures.

Table 7
Substitution rates for consonants and vowels (substitution errors only)

a. Percentage (and number) of consonants and vowels substituting for consonants and vowels

Stimulus	Response	
Letter type	Consonant	Vowel
Consonant	77 (358/468)	23 (110/468)
Vowel	85 (216/255)	39 (99/255)

b. Percentage (and number) of consonants and vowels substituting for consonants and vowels for lexical versus nonlexical errors

Stimulus	Lexical errors		Nonlexical errors	
Letter type	Consonant	Vowel	Consonant	Vowel
Consonant	84 (87/104)	16 (17/104)	74 (271/364)	26 (93/364)
Vowel	48 (26/54)	52 (28/54)	65 (130/201)	35 (71/201)

differed from what would be expected by chance, we again used the calculated proportions of consonants and vowels in the orthography. Combined with the assumption that letters are selected independently, the probability that a consonant will substitute for a consonant and a vowel for a vowel is given by the following equation: $(0.62 \times 0.62) + (0.38 \times 0.38) = 53\%$. Although this formula represents a low estimate, it can be seen that DS' preservation of C/V status is higher than that expected by chance ($\chi^2(1) = 14$, $p < .001$). This finding holds true for both lexical and nonlexical errors analyzed separately (Lexical Errors: $\chi^2(1) = 12$, $p < .001$; Nonlexical Errors: $\chi^2(1) = 6$, $p < .05$; see Table 7b). However, this finding should be interpreted with caution, as the formula used here to estimate error rates for consonants and vowels constitutes a low estimate. Furthermore, DS' rate of preservation of C/V status is significantly lower than those reported for patients with graphemic–buffer deficits (e.g., Jónsdóttir et al. (1996) report a C/V status preservation rate of 92% for their patient AS, and Ward & Romani (2000) report a C/V status preservation rate of 88% for their patient BA).

Geminate–singleton grapheme status. When a geminate was present in the target, DS reproduced a geminate sequence in 50% of the cases (19/38), but produced a geminate sequence in response to a nongeminate target in only 4% of the cases (6/160; see Table 8a). Therefore, DS selectively preserved gemination ($\chi^2(1) = 6.76$, $p < .01$). Furthermore, while the position of the geminate sequence in the target word

Table 8
Geminates

a. DS' % (no.) of responses containing a geminate for targets with and without geminates

Target type	
Geminate	Nongeminate
50 (19/38)	4 (6/160)

b. Number of DS' responses containing a geminate for targets containing a geminate, which preserved letter identity and/or letter position

Letter identity	Letter position		
	Same	Different	Total
Same	7	0	7
Different	9	3	12
Total	16	3	19

was preserved in 84% of the cases (e.g., kangaroo > KETERCTT) and not in the remaining 16% (e.g., needle > FARRES), the identity of the geminate sequence was preserved in only 14% of the cases, all of which also involved preservation of the position (e.g., glasses > TRASSAN), and not preserved in the remaining 64% (e.g., mushroom > HEgRKAAR) (see Table 8b). That is, information about the number of double letters was selectively preserved relative to information about the identity of the double letters ($\chi^2(1) = 9, p < .01$). This finding is consistent with the overall finding of preservation of number of graphemes in the face of disruption of their identity.

Mixed case. Of the 1114 letters produced by DS, 84% (931/1114) were in uppercase, and 16% (183/1114) were in lowercase. These were equally distributed across correct, lexical, and nonlexical responses (see Table 9).

Letter processing. To assess DS' ability to process letters in isolation, she was administered a series of single-letter tasks. DS was 40% (8/20) correct in writing letters to dictation. Her performance was not due to a failure in visual discrimination, as on letter matching of upper- and lowercase with one distractor she performed flawlessly (100% correct (51/51)), and on upper- to lowercase letter transcoding she only made errors which were failures to transcode to lowercase (e.g., G was transcoded as ⟨G⟩ rather than ⟨g⟩; 62.3% correct (48/77)). Of the errors produced in writing to dictation, 4 could be interpreted as either stroke, visually, and/or alphabetically related (e.g., N > Z, E > F, P > R, S > T). The remaining 8 errors bore no similarity to the target (e.g., Q > L). A summary of her performance on these tasks is reported in Table 10.

The evidence discussed so far clearly indicates that DS' spelling deficit arises at a postbuffer level of processing. Therefore, the finding of (at least) occasional lexical responses among DS' written spelling errors is surprising, as one would not expect lexical properties to affect her performance at this peripheral level. We have already seen that her lexical and nonlexical errors do not differ in terms of several properties, such as distribution across letter positions, or preservation of C/V status. Therefore, the lexical errors seem to arise from damage to the same mechanism that produces the nonlexical responses.

What determines the probability that a lexical error will occur? One possibility is that the lexical errors are stereotypical or perseverative responses. However, responses that appeared more than once were repetitions of responses that may have appeared many trials prior to the repetition or even in different sessions, and none of these responses represented the perseveration of an immediately preceding stimulus or response. Furthermore, only 24% (12/49) of the lexical responses could be

Table 9
Percentage (number) of upper- and lowercase letters produced by DS for the different response types

Response type	Uppercase	Lowercase
Correct	90 (43/48)	10 (5/48)
Lexical error	90 (198/221)	10 (23/221)
Nonlexical error	82 (690/845)	16 (155/845)
Total	84 (931/1114)	16 (183/1114)

Table 10
DS' performance in single-letter processing

Task	% (no.) correct	Error examples
Writing to dictation	40 (8/20)	Z > U Q > L S > T V > B
Matching	100 (51/51)	NA
Transcoding (upper- to lowercase)	62 (48/77)	G > G B > B N > N

interpreted as stereotypical responses, including the repeated production of both a particular response (e.g., shop) and its morphological variants (e.g., shop, shops). This interpretation is therefore not sufficient. To address the question of what determines the occurrence of the lexical errors we first looked at whether specific letters tended to be subject to an error more often than others. This effect may be expected if some letters were more difficult to execute (for example, because they require more strokes) or to discriminate (for example, because they share visual features with a larger number of letters). However, confusion matrices indicated no reliable pattern. Instead, a high correlation was found between the frequency of occurrence of a letter in the corpus and the frequency of error on that letter, indicating that letters that appeared more often in the corpus had a higher chance to undergo an error (Pearson's $r = 1$). When the letter frequency distribution in our corpus was compared against the letter frequency distributions in the English-orthography (Mayzner & Tresselt, 1965) a high correlation was also found (Pearson's $r = 0.9$), indicating that the corpus of words administered to DS is representative of the language. These findings indicate that letters were randomly subject to error.

DS' responses were also analyzed in terms of the frequency of the letters produced as an error. A significant positive correlation between the frequency with which a letter was produced as an error and the frequency of that letter in the corpus was found (Pearson's $r = 0.7$, $p < .01$; $r^2 = 0.5$). This finding indicates that single-letter frequency accounts for about 50% of the observed pattern of errors. Therefore, using the bigram frequencies reported by Solso, Barbuto, and Juel (1979), DS' responses were further analyzed in terms of the frequency (a measure of token frequency) and versatility (a measure of type frequency) of each bigram in the response. Both measures provide information about the probability with which a letter will occur after another letter. Overall, DS produced more frequently bigrams that are both more frequent and have higher versatility in the language (see Table 11a). The same pattern was observed when lexical and nonlexical responses were contrasted (see Table 11b). Because some of DS' nonlexical responses appeared to comprised a word plus additional letters (e.g., *shopn; *cookgant), we excluded these responses in order to eliminate any potential bias toward similar trends for words and nonwords. Even under these conditions, lexical and nonlexical responses exhibited the same trend with more frequent and more highly versatile bigrams being produced more often (see Table 12).

Table 11
Average frequencies and versatilities for bigrams produced once, twice, or more often in DS' response set

a. All responses

DS' rate	Frequency	Versatility	*N* bigrams
1	6,508	565	79
2	9,528	724	43
3–5	15,243	1146	45
>5	29,094	1802	47

b. Lexical versus nonlexical responses

DS' rate	Lexical responses			Nonlexical responses		
	Frequency	Versatility	*N* bigrams	Frequency	Versatility	*N* bigrams
1	7,238	1277	38	15,340	1020	228
2	26,838	1428	15	16,213	1111	62
>2	27,204	1965	17	29,900	1918	73

Table 12
Average frequencies and versatilities for bigrams produced once, twice, or more often in DS' lexical and nonlexical responses, excluding responses containing a lexical item

DS' rate	Lexical responses			Nonlexical responses		
	Frequency	Versatility	*N* bigrams	Frequency	Versatility	*N* bigrams
1	17,238	1277	38	12,290	831	123
2	26,838	1428	15	15,556	1048	38
>2	27,204	1965	17	28,756	1803	49

5. Discussion

We have presented the case of a patient with a deficit to written spelling processes in the face of preserved ability to orally spell and to accurately execute letter shapes. This case raises two main issues. First, what kind of processing mechanism is damaged in this patient, such that although she may be able to correctly spell the target item orally, she produces a written response comprising letters which bear no resemblance to those of the target? Second, what kind of processing mechanism do we need to assume is preserved in this patient, such that she is consistently able to produce a written response which has the same letter length as the target and respects bigram frequency distributions in the language?

We believe that the answer to the first question is relatively straightforward. DS' performance exemplifies a very clear dissociation—her oral spelling performance is virtually intact, whereas her ability to correctly spell words in the written format is virtually absent. Furthermore, we have clearly demonstrated that DS' written responses almost perfectly preserve the number of graphemes of the target word, and her errors show no serial position effect. This pattern can occur only if she has access to intact graphemic representations. In turn, for graphemic representations to be intact at the level of the graphemic buffer, knowledge of graphemic representations of words at the lexical level must also be preserved. This interpretation is corroborated by the finding that her errors are not affected by word frequency or regularity. Therefore, DS' spelling deficit cannot occur at or prior to the level of the graphemic buffer. We interpret the finding of intact graphemic representations at the level of the graphemic buffer as supporting the view that these representations are independent from the knowledge and processing of the motor–visual shapes used to represent letters in the written spelling modality (see Rapp & Caramazza, 1997).

We further take the well-formedness of DS' written responses as indication that the impaired processes are more central than those involved in peripheral aspects of motor control. As discussed in the Introduction, individuals with more peripheral deficits produce distorted or unrecognizable letters, involving insertion of additional or multiple strokes, misplacements of strokes, and so forth (e.g., writing "hammer" as *hamnmer* or "woman" as *uuonnam*; see Ellis, 1988; Margolin, 1984; or Rapp & Caramazza, 1997, for case examples). In contrast, DS never produced any errors that could be interpreted as stroke insertions or omissions, or unrecognizable letters.

In accordance with previous findings in patients with postbuffer deficits, DS' letter errors involve consonants and vowels alike, and include substitutions of consonants for vowels and vowels for consonants (e.g., DEER > EliS), the production of orthographically illegal letter sequences (e.g., DRIVE > bektg), and case mixing (e.g., LOBSTER > THogATS). These findings indicate that DS' spelling deficit arises at the level of processing that is dedicated to the assignment of letter shapes. However, her letter substitutions preserve to a significant extent information relative to the consonant–vowel status of the target letter as well as information about letter

doubling. The fact that gemination is preserved indicates that DS' responses are not a simple retention of length, but rather are sensitive to some structural elements of the word. Thus, it appears that (at least some) information about letter identities is retained and guides letter selection, but that the process of assigning specific letters to their corresponding positions in the word is disrupted. But the pattern of letter substitutions is not the result of random letter selection: DS' errors are affected by the frequency of letters in the language as well as by the transitional probabilities which specify the frequency of cooccurrence of letters in a bigram cluster.

What role may this information play and where may it reside in the writing system? The analyses of DS' lexical errors provide some information here. We have shown that DS' lexical and nonlexical errors arise from damage to the same post-lexical mechanism. Thus, the fact that lexical errors tend to occur only for shorter stimuli suggests that DS' errors are attempts at completing what she started writing. Under this interpretation, local adjustments may result in words for shorter stimuli, but lexicalization is much less likely for longer stimuli (and, in fact, if these responses were true lexical errors, they should occur at similar rates for shorter and longer words). That DS' lexical errors may be "repair" errors is also suggested by DS' production of responses that contain a lexical element, such as SHOPN or BUGKS. These may result from the convergence of length preservation and the production of more frequent, stereotyped letter sequences.

These findings indicate that a process which exploits local context information may be at play. By constraining the output, this mechanism would function to some extent as a repair system which locally inserts highly probable letter bigrams whenever a graphemic representation fails to select or activate subsequent representations necessary for correct written spelling. In so doing, this mechanism boosts the appearance of bigram frequencies and of the preservation of C/V structure. The functional location of such a repair mechanism is not clear. It is conceivable that it may result from the interaction of the visual, proprioceptive, or even attentional systems with the writing system. Although we have no measure of whether DS' bilateral cataracts affected her visual perception, it could be argued that DS' writing occurred under conditions of limited visual feedback. Under these conditions, it may be postulated that transitional and single-letter probabilities could be relied upon to constrain the written output.

An interpretation of this sort may be tenable even if DS' visual feedback were not limited. Indeed, studies of patients with so-called afferent or spatial dysgraphia seem to indicate that these patients' performance shows superficial similarities to that of normals writing with limited visual feedback. Furthermore, the responses of these patients do not become more defective when vision is prevented, indicating that these patients behave as if they do not use visual feedback for handwriting. This finding has also been interpreted more broadly as indicating that correct handwriting requires both visual and kinaesthetic feedback (Lebrun, 1976). However, findings from both normal and impaired subjects indicate that this cannot be the whole story. For example, Teasdale et al. (1993) reported the case of a patient with a total loss of touch, vibration, pressure, and kinaesthesia who could correctly produce the shapes of letters when writing with his eyes closed. Smyth and Silvers (1987) found that, in normal subjects, the occurrence of omission and repetition of strokes and letters increased not only when vision was prevented by the use of a screen, but also when subjects wrote while maintaining visual control and simultaneously articulating an irrelevant word ("blah") at a constant rate. This result indicates that visual feedback is no more necessary than broader capacities such as attention.

It is clear that more detailed theories of peripheral processes in writing are needed, articulating the nature of such representations as well as their interactions with other

systems such as the visual and the proprioceptive. What seems a necessary conclusion is that DS' pattern of responses calls for a postlexical, postgraphemic buffer account, and that information about transitional letter probabilities may play a remedial role at this level of processing.

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