

The Status of Double Letters in Graphemic Representations

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This paper addresses the issue of the structure of graphemic output representations via an analysis of the spelling performance of a patient with acquired dysgraphia. It is argued that the patient's pattern of performance with words that contain double letters (e.g., "bb" in "rabbit") is inconsistent with the view that graphemic representations are simple linear sequences of graphemes (or abstract letter identities). Rather, it is proposed that graphemic representations are multidimensional structures that separately encode information about grapheme identity and grapheme quantity. © 1996 Academic Press, Inc.

The main objective of this article is to provide, through the detailed analysis of the impaired spelling performance of a brain-damaged patient, converging evidence in support of the claim that the graphemic representations used in the course of spelling do not merely consist of a linear sequence of graphemes or abstract letter identities but are multidimensional mental objects that represent different aspects of graphemic structure. More specifically, we will argue that the pattern of performance reported here

confirms earlier proposals of a special representational status for double-letter sequences (e.g., "ee" in "green").

Despite the fact that spelling skills obviously constitute one of the major human cognitive abilities, their study has been relatively neglected in cognitive psychology; this is especially apparent if one compares this domain of investigation to others such as word recognition or oral reading. However, this situation has been evolving rapidly in recent years, since an increasing number of studies have been carried out in an attempt to elucidate various aspects of the spelling process; these attempts have sometimes relied on the analysis of normal subjects' misspellings (or "slips of the pen"; see papers in Ellis, 1979; Frith, 1980; Hotopf, 1983; Wing & Baddeley, 1980), on the analysis of children's misspellings (Read, 1986; Treiman, 1993), and mostly on the analysis of the various patterns of impaired spelling performance that can be observed in cases of acquired dysgraphia (e.g., Beauvois & Derouesné, 1981; Bub & Kertesz, 1982; Ellis, 1982, 1987; Goodman & Caramazza, 1986; Morton, 1980; Shallice, 1981; Patterson, 1987). These studies have allowed the formulation of more specific theories of the functional architecture of the spelling system, i.e., of the various processing components involved in spelling. In addition, specific hypotheses have been proposed about the nature of the

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representations computed at various levels of the spelling process.

Until recently, the most commonly entertained assumption regarding the structure of output graphemic representations was that they merely consisted of a linear sequence of abstract letter identities (e.g., Caramazza, Miceli, Villa, & Romani, 1987; Wing & Baddeley, 1980). However, there is evidence which suggests that graphemic representations may specify more than just the identity and order of graphemes. First, the performance of certain dysgraphic patients is constrained by the consonant/vowel status of the graphemes to be produced (Caramazza & Miceli, 1990; Cubelli, 1991; McCloskey, Badecker, Goodman-Shulman, & Aliminosa, 1994). For example, patient LB (Caramazza & Miceli, 1990) virtually always substituted consonants for consonants and vowels for vowels (children beginning to spell also tend to substitute vowels for vowels and consonants for consonants, see Treiman, 1993). Furthermore, his exchange errors (e.g., *vagone* → *gavone*) always involved consonants with consonants and vowels with vowels. Second, it has been shown in several patients (patient LB, Caramazza & Miceli, 1990; patient HE, McCloskey et al., 1994; patient SFI, Miceli, Benvegnù, Capasso, & Caramazza, 1995; patient EZ, Venneri & Cubelli, 1993) that adjacent double-letter sequences (such as “bb” in “rabbit”) have a special status in graphemic representations. For example, both LB and HE often substituted or exchanged letters in a word but rarely did so when letters were part of a double-letter sequence (e.g., they were likely to produce errors such as *basket* → *BALKET* or *basket* → *SABKET* but not errors such as *rabbit* → *RALBIT* or *rabbit* → *BARBIT*). Also, both patients frequently produced errors like *rabbit* → *RABITT* in which another letter of the word was doubled. These and other observations suggest (1) that double-letter sequences behave as units and (2) that information about grapheme quantity is encoded separately from information about grapheme identity. It is important to note that LB and HE’s patterns of performance were not tied to a particular modality of output: Results were similar whether they involved written spelling or oral spelling, consistent with the

view that they reflect properties of abstract graphemic representations.

Other studies have also shown special effects of letter doubling in spelling performance but these effects cannot unambiguously be considered to reflect representational distinctions at the level of graphemic structure. Studies of skilled typing in normal subjects suggest that double-letter sequences differ at some level from other letter sequences. For example, several researchers (Rumelheart & Norman, 1982; Shaffer, 1975; Shaffer, 1976) have reported the occurrence of errors in which the wrong letter is being doubled (e.g., *rabbit* → *RABITT*). However, these studies did not demonstrate that such errors were systematically related to the presence of a double-letter sequence in the target word. In addition, it is not possible to determine whether these errors occur at the level of graphemic representations or at some more peripheral (e.g., motor) level.

Another line of evidence suggesting a special representational status for double-letter pairs comes from the study of the timing of strokes in typing random letter strings (Sternberg, Knoll, & Turock, 1990; Sternberg, Knoll, Monsell, & Wright, 1993). These studies have shown that the time interval between strokes is a linear function of the number of letters in a string. Interestingly, these studies have also shown that the length of the interval between strokes in a string containing, say, five letters, one of which is doubled (e.g., *CRBBT*), is equal to the length of the interval between strokes in letter strings containing four different letters (e.g., *CRBT*). In addition, these studies demonstrated that the interval between the doubled letters themselves was independent of the length of the string. These results suggest that double-letter sequences behave as units but, as in the case of the typing error data, they do not directly address the question of the structure of abstract graphemic representations because they could reflect properties of more peripheral levels of representation. In fact, Sternberg et al. (1983) consider their data as reflecting properties of motor programs.

Finally, although the performance of dysgraphic patients VB (Ellis, Young, & Flude, 1987) and RT (Venneri, Cubelli, & Caffara,

1994) revealed specific effects associated with letter doubling, the results are nonetheless neutral with respect to the question of the structure of graphemic representations. The majority of VB's errors involved the addition or deletion of letters in the context of double-letter sequences (e.g., rabbit → RABIT or rabbit → RABBBIT). However, Ellis et al. (1987) show that these errors do not arise due to impaired knowledge of the graphemic representations to be produced but rather as a consequence of impaired visual and kinesthetic feedback mechanisms. Similarly, Venneri et al. (1994) were able to show that their patient's selective perseverative errors with double letters (e.g., ragazzo → RAGAZZO; intelletto → INTELLETTTITTO) arose at a post-graphemic level of processing.

Different proposals have recently been put forward to account for the structural constraints observed in the performance of dysgraphic patients with damage at the level of graphemic representations. Central to these proposals is the notion, borrowed from autosegmental phonology (e.g., Clements & Keyser, 1983), that graphemic representations are multidimensional mental objects. This means that different dimensions of a graphemic representation are encoded separately. Caramazza and Miceli (1990) have proposed that orthographic representations consist at least of a Consonant/Vowel status (CV-status) tier and a grapheme identity tier. Structures of this type can be schematized as in (1).

(1) C V C C V C
 | | | | |
 b a s k e t

Caramazza and Miceli's proposal also posits the existence of a special feature for representing letter doubling information. Within this framework, the structure of double-letter words can be schematized as in (2).

(2) C V C V C
 | | | | |
 r a b i t
 |
 D

One implication of the representational assumption in Caramazza and Miceli is that different dimensions of graphemic representations can be selectively affected by damage. The aim of this paper is to provide additional evidence in support of the claim that double-letter sequences have a special status within graphemic representations. More specifically, we will examine the claim that information about grapheme identity and information about grapheme quantity are represented as independent dimensions of these representations. Support for this claim will in turn be taken as support for the more general view that graphemic representations are complex multidimensional structures rather than simple linear sequences of letter tokens.

CASE REPORT

Patient FM, a right-handed male and a high school graduate, suffered a large infarct of the left middle cerebral artery at age 36, 10 years prior to this study. A CT scan performed 2 years later revealed a large area of damage involving the infero-posterior frontal lobe, the inferior parietal lobe, and the anterior temporal lobe of the left hemisphere, as well as the underlying white matter and lateral basal ganglia; there was also evidence of cortical atrophy of the remainder of the left frontal convexity.

At the time of this investigation, FM presented with a right hemianopia (that he compensated for), a moderate right spastic hemiplegia affecting predominantly the upper limb, and a still severe language impairment. His oral expression was laborious and was characterized by "telegraphic" speech, word finding difficulties, phonetic/phonological errors, as well as some morphological errors. In addition, some semantic errors were observed in oral picture naming tasks. Oral comprehension was comparatively very well preserved (although sentence-picture matching tasks showed signs of "asyntactic" comprehension; see Badecker, Nathan & Caramazza, 1991, for an analysis of FM's sentence comprehension deficit).

FM's performance in reading aloud was severely impaired, especially for long, abstract, and low frequency words. His performance was

also affected by the grammatical category of the test items (nouns were read better than adjectives which were read better than verbs which were read better than function words); his capacity to derive nonlexical phonology from print, as assessed by asking him to read nonsense words, was severely impaired. His errors in reading words included numerous visual (notion → LOTION), semantic (deaf → MUTE), visual/semantic (chord → CHORUS), and morphological (hungry → HUNGER) errors (for more details concerning FM's reading impairment see Badecker & Caramazza, 1987; Gordon, Goodman-Shulman, & Caramazza, 1986).

Even more severely impaired was the patient's spelling performance, which is the focus of the present report.

SPELLING PERFORMANCE

Most of the analyses we will present are based on FM's responses to a corpus of 2044 words presented in isolation. Of these words, 823 were presented in a written spelling-to-dictation task, 379 in a written picture naming task, and 842 in a delayed copy transcoding task. In this last task, the patient had to write in uppercase characters a word that was shown to him in lowercase characters and then removed from his sight. Responses to these stimuli were collected over a period of approximately 15 months (from July 1991 to November 1992). Due to his right-sided hemiparesis, FM used his left hand to write. To facilitate scoring procedures, he was asked to always write in uppercase characters. The letters he produced were always well formed. In spelling to dictation, he was also asked to repeat each word aloud before writing it down, so as to ensure that he perceived it correctly; other than some articulatory difficulties, there were very few errors in his repetition performance. FM was also asked to indicate which words, if any, were unknown to him; these very few cases were excluded from further analyses. The second occurrences of words inadvertently presented twice in the same task were excluded as well. Also, there were a few cases in which FM either produced a multiple-word response or an abbreviation. There were 11 such errors in the written picture nam-

ing task (e.g., snail → NEET TOLLIC), 2 in the spelling to dictation task (e.g., television → T.V.), and none in the delayed copy transcoding task; they were all excluded from further analyses. FM was quite aware of his spelling problem and tended to make more than one attempt at writing a word; we limited our analyses to the first complete response produced on each trial. All the stimuli used in the written picture naming and delayed copy transcoding tasks were also presented in the spelling-to-dictation task so that direct comparisons across tasks could be made when necessary.

The errors that FM produced were organized into six categories (examples of each error type are presented in Table 1):

One category included semantic errors. These include cases in which there existed some degree of semantic relationship between the target word and the response produced. Assignment of items to this category was not unequivocal however, due to the fact that many of the patient's responses were so deviant (e.g., triangle → ZUALECT) that it was difficult to determine which word the patient was actually trying to produce. For this reason, only cases in which at least two out of three independent judges agreed were scored as semantic errors. Thus, it is probable that a number of semantic errors were included in one of the other categories because we could not determine which target FM was trying to spell.

A second category included phonologically plausible errors, that is, responses that constituted an erroneous but possible orthographic realization of the target's phonology (i.e., when it would be possible to read the response as an homophone of the target, e.g., belief → BE-LEAF).

The remaining errors were divided into categories on the basis of whether the response was a word or a nonword and whether it was orthographically similar to the target or not; targets and responses were considered orthographically similar when they shared at least half of their constituent letters, in any order. These last four categories were thus the following: orthographically similar word errors, orthographically dissimilar word errors, orthographically similar

TABLE 1
EXAMPLES OF THE DIFFERENT TYPES OF ERRORS FM
PRODUCED IN THE THREE SPELLING TASKS

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1. Semantic errors
carton → BOX
donkey → DEER
crocodile → ALLITOR (ALLIGATOR)
lamp → TALBE (TABLE)
 2. Phonologically plausible errors
belief → BELEAF
pitcher → PITCHUR
father → FATHAR
cattle → CATTEL
 3. Orthographically similar word errors
hoe → HOLE
lion → LOIN
shower → SHORE
button → BUTTER
 4. Orthographically dissimilar word errors
row → STAIN
moment → BUT
beard → BANK
ladder → HARROW
 5. Orthographically similar nonword errors
pea → PAE
mule → MUKE
grapes → GPAGE
moment → MOMUOT
 6. Orthographically dissimilar nonword errors
fate → FRICH
sink → ZIGE
radish → TIPLOGE
magnolia → MOBIHOEY
-

Note. Our assumption about FM's intended target, when different from the stimulus, is shown in parentheses.

nonword errors, and orthographically dissimilar nonword errors.

Table 2 summarizes the results obtained, reporting global error scores as well as the distribution of error types for all stimuli in each task as well as for a subset of stimuli that were presented in all three tasks.

Performance in all tasks was mainly characterized by numerous substitutions, omissions, additions, and/or reorderings of letters, leading predominantly to the production of nonhomophonic nonword errors that shared various degrees of orthographic similarity with the targets. As shown in Table 2, FM also produced a small proportion of errors that were semantically related to the target. Performance in de-

layed copy transcoding was better than in the other two tasks (37% errors only on a set of stimuli that resulted in 65% errors in spelling to dictation and 66% errors in written picture naming). Errors in this task also tended to be closer to the targets (the proportion of orthographically similar errors was much higher) and very few semantic errors were observed. In addition to these three tasks, FM was also given a set of 62 lowercase printed items to reproduce in uppercase characters. This direct copy transcoding task was taken from the Johns Hopkins University Dysgraphia Battery (Goodman & Caramazza, 1985); it includes 42 words of different grammatical categories and 20 legal nonwords. Performance on this task was flawless.

FM's spelling performance was affected by various factors. First, we observed that performance in all tasks deteriorated markedly as a function of increasing stimulus length (see Fig. 1). Second, the probability of a letter being involved in an error varied as a function of its position within the word: FM was most likely to produce the initial letter of a target word and least likely to produce letters in medial positions; this serial position effect is illustrated in Fig. 2 for five-letter words presented in spelling to dictation. Third, letters from the target were more likely to appear in the response if they were vowels than if they were consonants (71% versus 57% for six-letter words). In addition, FM's performance on tasks of the Johns Hopkins University Dysgraphia Battery (Goodman & Caramazza, 1985) indicated that three other factors affected his probability of making an error. One of them was word frequency: FM spelled 32/55 high frequency words correctly while he only spelled 10/55 low frequency words correctly ($\chi^2(1) = 18.8, p < .001$). Also, his performance with nonwords (0/34) and closed-class words (0/20) was worse than his performance with open-class words (nouns, verbs, and adjectives: 15/84). FM also showed a small tendency to be better on words with common sound-to-spelling correspondence (14/30, 47% correct) than on words with uncommon sound-to-spelling correspondence (28/80, 35% correct) but this difference did not reach significance ($\chi^2(1) = 1.2, p > .05$).

TABLE 2
PERCENTAGES OF ERRORS OF DIFFERENT TYPES IN THREE SPELLING TASKS

	Spelling to dictation (<i>n</i> = 823)	Written picture naming (<i>n</i> = 379)	Delayed copy transcoding (<i>n</i> = 842)
Total set			
Errors	76	66	54
Semantic	11	16	2
Phonologically plausible	2	1	3
Orthographically similar word	6	8	4
Orthographically dissimilar word	3	2	0
Orthographically similar nonword	47	58	84
Orthographically dissimilar nonword	32	15	7
Matched set			
Errors	65	66	37
Semantic	7	16	1
Phonologically plausible	2	1	4
Orthographically similar word	7	9	5
Orthographically dissimilar word	1	2	0
Orthographically similar nonword	59	58	84
Orthographically dissimilar nonword	25	15	6

Note. To allow a better comparison across tasks, the matched set presents the data from a subset of stimuli that were presented in all three tasks (*n* = 370).

Considered together, these data suggest that FM's disturbed spelling performance results from a combined impairment of (1) the graphemic buffer, (2) the lexical-semantic component

and/or orthographic output lexicon, and (3) the phonology to orthography conversion mechanism. The flawless performance in the direct copy transcoding task suggests that representa-

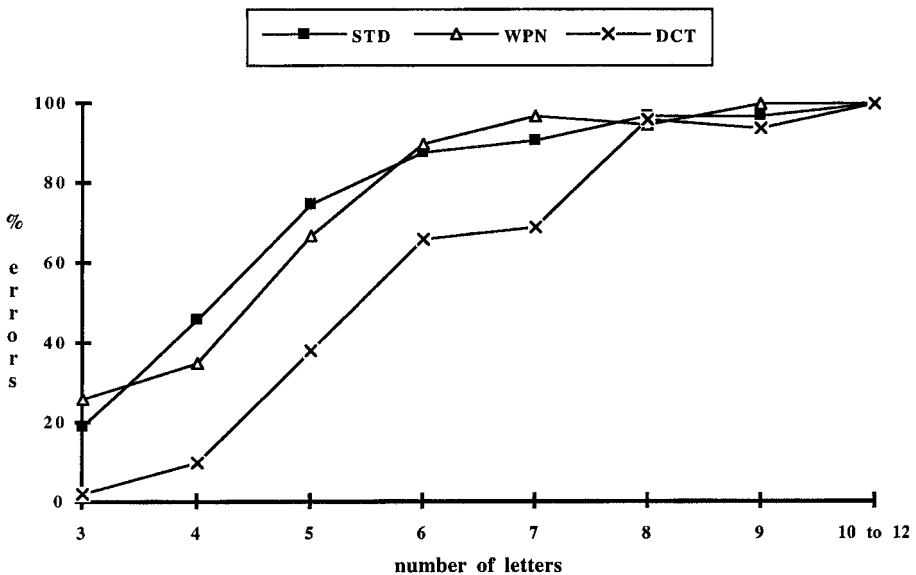


FIG. 1. Percentage of errors as a function of word length in spelling to dictation (STD), written picture naming (WPN), and delayed copy transcoding (DCT).

DOUBLE LETTERS AND GRAPHEMIC REPRESENTATIONS

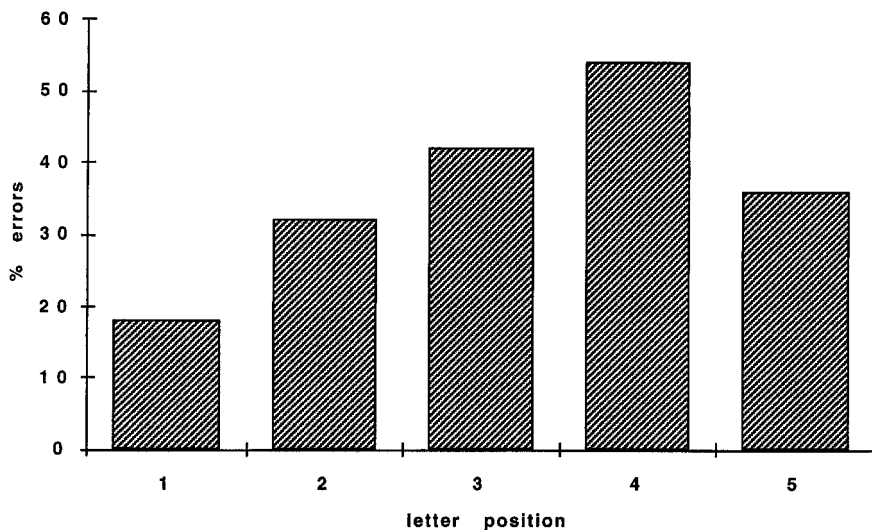


FIG. 2. Percentage of errors on individual letter positions in five-letter words produced in spelling to dictation.

tions and processes located downstream from the graphemic buffer were intact. There are various aspects of FM's spelling performance that are consistent with the hypothesis of a graphemic buffer impairment (see Caramazza et al., 1987; Caramazza & Miceli, 1990; Hillis & Caramazza, 1989; Posteraro, Zinelli, & Mazucchi, 1988). First, all tasks which, according to the model presented in Caramazza et al. (1987), require the information to be tempo-

rarily stored in the graphemic buffer were affected by damage (i.e., spelling to dictation, written picture naming, and delayed copy transcoding; FM was also unable to perform oral spelling to dictation). Second, most errors in these tasks involved the misselection or misordering of graphemes; this type of error is typical of graphemic buffer impairments. Table 3 presents the distribution of letter substitutions, deletions, additions, and movement errors for

TABLE 3
PERCENTAGES OF SINGLE ERRORS AND THEIR DISTRIBUTION IN THE THREE SPELLING TASKS

	Spelling to dictation (total errors = 629)	Written picture naming (total errors = 248)	Delayed copy transcoding (total errors = 453)
Single errors	11%	23%	37%
Substitutions	57%	60%	67%
	neck → NEAK	moon → MOOR	panel → PADEL
	template → TEMENTLE	puma → PUNA	unit → UNIN
Deletions	23%	28%	19%
	boost → BOOT	church → CHUCH	apricot → APICOT
	kitchen → KITHEN	drawer → DAWER	beetle → BEELE
Movement	13%	12%	11%
	lemon → LENOM	chain → CHIAN	planet → PLAENT
	turkey → TUKERY	heart → HREAT	ground → GRONUD
Additions	7%	0	3%
	fence → FEINCE		beauty → BEAUNTY
	sweet → STWEET		aggress → AGGORESS

responses that included one and only one of these errors. It appears that this distribution is remarkably similar across tasks, as would be expected. Third, the dramatic length effect presented in Fig. 1 is consistent with a graphemic buffer deficit. Fourth, as in other documented cases of graphemic buffer impairment, we observed that the probability of a letter being involved in an error varied as a function of its position within the word (see Fig. 2).

The fact that FM produced semantic errors in all tasks involving semantic mediation independently of the modalities of input or output (i.e., spelling to dictation, written picture naming, reading aloud, oral picture naming) also suggests an impairment of the lexical-semantic component. An additional impairment at the level of the orthographic output lexicon cannot be ruled out (and may be suggested by the existence of a word frequency effect).

There are various reasons to suspect an additional impairment of the phonology-to-orthography conversion mechanism. First, FM's performance with nonword stimuli appeared to be worse than his performance with words. Second, one may have expected that performance in spelling to dictation would have been better than performance in written picture naming if additional information coming from the nonlexical route to spelling was available to him; this was not the case. Also, if FM was making use of such a mechanism, one would expect the number of phonologically plausible errors to be higher than it is, or at least higher in the spelling to dictation task than in the written picture naming task; this was not the case either.

One very striking aspect of FM's spelling performance was the apparent preservation of double letter information (hereafter "DL information"). That is, it was our impression that, even when information about letter identity and order was extremely distorted, FM's responses tended to include a double letter sequence when there was one in the target word (e.g., giraffe → GAFFICATE; raccoon → REAFFIC). The results of the analysis reported in Table 4¹ show

¹ All semantic errors were excluded from this as well as all later analyses; the reason for this is that one would not expect to observe a preservation of any aspect of the internal

that this preservation of doubling did not merely reflect a bias to produce DL sequences, irrespective of the structure of the targets: Although FM did produce some DL sequences in response to targets without DL sequences,² he was much more likely to do so if the target contained a DL sequence. This observation raises the possibility of a special status for double letters in graphemic representations. With this consideration in mind, we decided to explore further FM's spelling performance, focusing on his performance with double-letter sequences.

FURTHER ANALYSES OF THE APPARENT PRESERVATION OF DOUBLE LETTER INFORMATION

Distinct Predictions of the Multidimensional versus Linear Sequence Hypotheses

According to the linear sequence hypothesis, the structure of the graphemic representation of words with double letters does not differ from the structure of the representation of words without double letters: In both cases, it simply consists of an ordered set of graphemes (or abstract letter identities). Following this hypothesis, one would not expect DL sequences to behave any differently from otherwise comparable sequences of letters (what we mean by "otherwise comparable" will be made explicit below). According to the multidimensional hypothesis, on the other hand, the structure of DL words does differ from the structure of non-DL words. The nature of this difference can be stated as follows: Whereas all nondouble letters of a word are connected to distinct units on the

structure of the target when, as in cases of semantic errors, the wrong lexical unit was retrieved from the orthographic output lexicon.

² Recall that we concluded that the corpus might include a number of semantic-then-graphemic errors that could not be identified as such by all our judges; it is therefore quite likely that some, maybe even most, of the DL responses to non-DL targets occurred as a consequence of this type of error when the semantically related word that the patient was trying to spell happened to include a DL sequence, as may for example be the case in elephant → (giraffe ?) → ROTIGGE.

identity tier, DL pairs are connected to only one such unit; the fact that this particular letter identity appears twice contiguously in the word is specified at another level of the representation.

As mentioned previously, this particular organization of information implies that, contrary to what would be expected within the linear sequence hypothesis, the behavior of DL sequences should differ from that of otherwise comparable letter sequences. However, the exact way in which these two types of letter sequences should differ may well vary as a function of the nature and/or the extent of the damage affecting graphemic representations: Is damage generally limited to one level of representation (i.e., the letter identity level, the letter doubling level)? Does it generally affect both levels but in an asymmetrical way? Does it involve a loss of identity information for some representations and of doubling information for some others? Or both? Taken at face value, FM's impaired spelling performance suggests that the letter identity level is often impaired (see for example the high number of letter substitutions) and that doubling information is often preserved (see Table 4). *Under these circumstances*, and given the central assumption that double letter sequences are associated to a single letter identity, one would expect FM's performance with double-letter sequences to exhibit at least the two following characteristics: (a) double-letter sequences will tend to behave as units, and (b) there will be cases in which doubling information will be preserved independently from letter identity.

In the remainder of this section, we will examine each of these predictions in turn. Notice that neither of these follows from the linear sequence hypothesis because it does not give any special status to DL sequences. Therefore, confirming these predictions will be taken as direct evidence in favor of the multidimensional hypothesis and against the linear sequence hypothesis.

Comparable Letter Sequences

As noted above, the linear sequence hypothesis predicts that, *everything else being equal*, performance with double-letter sequences should not differ from performance with other letter sequences. This means that evaluating the adequacy of the linear sequence hypothesis requires controlling for any factor other than the presence versus the absence of doubling that may affect performance on any given sequence of letters; in other words, it critically depends on the selection of appropriate control sequences for DL sequences. Given what we know about the factors that affect FM's spelling, performance with double-letter sequences should be compared to performance with non-double-letter sequences that are equivalent in terms of (a) the length of the words in which they are embedded, (b) the word position of the sequences examined, and (c) their consonant/vowel status.

It is possible that the apparent preservation of DL information that we have reported earlier may merely have reflected the influence of one or more of these factors. This will not be the

TABLE 4
PRESENCE OF DOUBLE LETTERS IN ERROR RESPONSES AS A FUNCTION OF THEIR PRESENCE OR ABSENCE IN THE TARGETS IN THREE SPELLING TASKS

	Targets with one double letter	Targets with no double letter	$\chi^2(1)=$
Spelling to dictation	68% 86/126	15% 60/411	142.0
Written picture naming	87% 41/47	11% 17/161	107.6*
Delayed copy transcoding	92% 97/105	3% 9/349	363.9*

* $p < .0001$.

case in the analyses that will follow where performance with DL sequences will always be compared to performance with pairs of non-doubled contiguous letters, of identical consonant/vowel status, appearing in the same position of words of identical length (e.g., the behavior of double-letter sequences such as “bb” in “rabbit” will always be compared to the behavior of sequences such as “sk” in “basket”). Given that the matching of DL pairs to their controls was undertaken a posteriori and given that the total number of stimuli with a DL sequence was much lower than the total number of stimuli without a DL sequence, there often was more than one possible control word for each DL word. In light of this, our strategy was to arbitrarily select, for each DL target, one non-DL target that satisfied our matching criteria. There also were cases where no adequate control word could be found for a DL word; these cases were not analyzed.³

Do Double Letters Behave as Units?

This question can be addressed in two different ways. One is to look at the probability of FM producing errors that split a letter sequence (e.g., rabbit → RABTIB; basket → BASTEK). According to the linear sequence hypothesis, this probability should be equivalent for DL sequences and their controls. According to the multidimensional hypothesis on the other hand, this probability should be lower for double-letter sequences than for control sequences: Given that DL sequences are represented by a single grapheme, movements errors should involve both letters of the sequence such as in rabbit → RATIBB (where both the grapheme identity and the doubling feature move to another position in the word) or rabbit → RATTIB (where doubling information stays in place but where there is an exchange of the grapheme identities “b” and “t”).⁴ Explaining errors

such as rabbit → RABTIB within the multidimensional framework involves postulating a complex combination of errors: In the example above, one would have to say that (1) the letter “b” in position 4 was deleted (via a deletion of the doubling feature), (2) the letter “t” was shifted from position 6 to position 4, and (3) a letter was inserted in final position that happened by chance to have the same identity as the deleted letter (b). The probability of such a combination of events would seem to be quite low. Within this framework, one would thus expect that the number of errors producing a split in a sequence should be lower for DL sequences than for control sequences. Testing this hypothesis requires that the patient produce a large enough number of “splitting” errors on either type of letter sequences. This was only the case in the corpus gathered in the spelling-to-dictation task. In this corpus, there were 165 control words that could be matched to 165 double-letter words. Within this subset, 13 “splitting” errors were observed in responses to control targets (e.g., barn → BRON, walnut → WALAEN, turkey → TUKERY, patriotic → PATORINY); however, no such errors were produced in responses to double-letter targets. This difference in the production rates of “splitting” errors ($\chi^2(1) = 13.6, p < .001$) provides a first piece of evidence against the linear sequence hypothesis.

Another way to examine the hypothesis that DL sequences behave as units is to look at the relative probabilities of FM’s responses including only one of the two letters of a sequence as a function of target type (e.g., rabbit → RABIT, basket → BAKET). If, as we argued earlier, FM’s failure to produce some of the letters of a target is related to a failure to retrieve units at the level of the grapheme identity tier (or to keep them active long enough) while his impairment often spares doubling information, then one would expect, on the hypothesis that double-letter sequences are represented by a single grapheme, that failure to produce double letters will be of the all-or-none type. In other words, the following situations may often occur: (a) doubling information is preserved and grapheme identity is correctly specified, in

³ All analyses reported in this paper have been carried out more than once with different arbitrary pairings; the results obtained were very similar. In each case, we chose to report the last analysis performed, whether or not it produced the strongest pattern of results.

⁴ FM did produce some errors of this type, e.g., cherry → CHREEY, parrot → PATTOR, bottle → BOLLET.

which case both letters will be produced, or (b) doubling information is preserved and grapheme identity is incorrectly specified, in which case none of the letters will be produced. Therefore, the probability of FM producing only one letter of a pair may be lower for DL pairs than for control pairs.⁵ We tested this hypothesis by comparing the number of responses that included one and only one letter of a target sequence for all DL targets for which we could find matched control targets. Note that our selection criterion only concerned the presence or the absence of a particular letter in a response; whether it appeared in the correct position or not was not taken into consideration. Some examples of the types of responses used in this analysis are provided in Table 5; the results themselves are presented in Table 6.

These results reveal the presence of a clear asymmetry in the distribution of responses as a function of target type: As expected, there were many fewer responses that included only one letter of a sequence in the case of DL targets than in the case of control targets, and this in all spelling tasks.

⁵ Note that the opposite prediction could be made for other patients. That is, there may exist patients whose impairment involves a frequent deletion of doubling information. In this case, one would expect that the probability of producing only one letter of a pair should be higher for DL sequences than for control sequences. Patient SFI (Miceli, Benvegñù, Capasso, & Caramazza, 1995) shows this pattern.

Discussion. The previous set of analyses shows that performance with DL sequences differs from performance with otherwise comparable letter sequences in at least two respects. First, the letters that belong to double-letter sequences are less likely to be erroneously produced in nonadjacent positions than the letters from otherwise comparable sequences. Second, FM is less likely to produce only one of two letters if these letters form a double-letter sequence than if they do not. These results are inconsistent with the linear sequence hypothesis. Moreover, they suggest that DL sequences behave as units, a finding that is readily accounted for on the hypothesis that DL pairs are associated to a single unit on the identity tier of graphemic representations.

Is Quantity Information Preserved Independently from Identity Information?

As stated earlier, another prediction that follows from the hypothesis that information about grapheme identity and information about grapheme quantity are represented independently within graphemic representations is that damage to such representations may affect identity information without affecting quantity information. If this were the case, one may expect to observe errors such as rabbit → RADDIT, rabbit → RATTIB, or rabbit → RABITT in which doubling occurs on the wrong letter identities. This is because damage to graphemic represen-

TABLE 5
SOME EXAMPLES OF THE TYPES OF STIMULI INCLUDED IN THE ANALYSIS REPORTED IN TABLE 6

	Double-letter words	Control words
One letter produced	bottle → BOLLET ribbon → B ROLLOW sheriff → S IFEAR cherry → CHREEY gorilla → GOLIFFE stubborn → B ALEINHT	hanger → NEATS monkey → MOKEY ostrich → QCTBELL costum → COTUMN bridge → BLIGORY guitar → GIATHOT
Zero letters produced	taffy → TAPPY skull → SKUCH pioneer → PALLOOM	perk → PITE swing → SWOCH resist → BELAIRLD
Two letters produced	butter → BUTTER spool → STOOP umbrella → UMALLOW	donkey → DONKEY kitchen → KITCHAR turkey → TUKERY

Note. Critical letters are typed in boldface.

TABLE 6
PROPORTIONS OF RESPONSES THAT INCLUDE ONE AND ONLY ONE LETTER OF A TARGET PAIR FOR DOUBLE-LETTER PAIRS
VERSUS MATCHED CONTROL PAIRS

	Double-letter targets (e.g., <i>rabbit</i>)	Control targets (e.g., <i>basket</i>)	$\chi^2(1)=$
Spelling to dictation	.15 24/165	.41 68/165	29.2*
Written picture naming	.09 6/69	.39 27/69	17.6*
Delayed copy transcoding	.07 13/183	.33 60/183	37.8*

* $p < .001$.

tations may either be such that (a) doubling information is preserved while information about the position of some graphemes is lost (which may lead to errors like *rabbit* → *RATTIB*), or (b) doubling information is preserved while some graphemes are misselected (which may lead to errors like *rabbit* → *RAFFIT*), or (c) doubling information is preserved but assigned to the wrong position in the word (which may lead to errors such as *rabbit* → *RABITT*). Consistent with this view, FM's corpus included a number of errors of this type; some examples drawn from each task are shown in Table 7. We would like to point out that FM's production of errors of this type was not limited to the written output modality. It was not possible to test oral spelling with him due to a severe impairment in single letter naming. However, when a typed alphabet was placed in front of him FM was capable of pointing to the sequence of letters that he thought formed the spelling of a dictated word. The errors he produced in this task ($n = 29/39$) were qualitatively similar to the ones obtained in tasks involving written production, including with respect to double-letter sequences (e.g., *egg* → *EEG*, *parrot* → *PETTOT*, *umbrella* → *UMINMMO*).

The mere presence of a relatively large number of such errors is interesting but alone is not sufficient to make the case for the independence of letter quantity information from letter identity information. This is because FM also produced DL sequences in response to non-DL targets. Therefore, it still needs to be shown that erroneous DL sequences occur more frequently on DL targets than on non-DL targets.

We addressed this question by considering all the responses to DL targets in which either one or both letters of a critical target pair was not produced. These DL items were matched to

TABLE 7
EXAMPLES OF THE DIFFERENT TYPES OF RESPONSES
CONSIDERED IN THE ANALYSIS REPORTED IN TABLE 8

- DL words where the patient failed to produce at least one of the double letter (in any position) and:
 - Another DL sequence was produced
hammer → *HARRON*
ghetto → *GHOTEE*
umbrella → *EMMUCEPE*
jazz → *JAFF*
slipper → *SLIDDEN*
ribbon → *BROLLOW*
 - No DL sequence was produced
fizz → *FROCK*
putt → *POT*
cheek → *COMDER*
zipper → *SALOBLE*
gorilla → *GONAGAL*
stubborn → *BALEINHNT*
- Control words where the patient failed to produce at least one of the letters of the matched sequence and:
 - A DL sequence was produced
oath → *OTTA*
hanky → *NINNIE*
streak → *STEET*
harp → *ADDIM*
cling → *OTHTER*
morphine → *MAGETTE*
 - No DL sequence was produced
sock → *SOCP*
monkey → *MOKEY*
shoulder → *SLATOR*
hawk → *HOAF*
hanger → *CHIAK*
chipmunk → *CIMPEOT*

control words which, in addition to the criteria previously specified, also led to responses in which at least one letter of the critical sequence (e.g., *basket*) was missing. We then determined how often a DL sequence was produced for DL targets versus matched control targets. We thus compared the probability of the patient producing errors like *rabbit* → RATTIB, or *rabbit* → RAGGIT, in which one or two of the letters of the original DL sequence are missing but a DL is produced anyway, versus errors such as *basket* → BAKKET or *basket* → BAMMET, in which one or two of the letters forming the original matched control sequence are missing and a DL is added. The finding that DL sequences occur more frequently in response to DL targets within this particular subset of errors would substantiate the claim that doubling information can be preserved independently from information about the letter identities it is normally tied to. The results of this analysis are presented in Table 8.

Once more, the results of this analysis support a prediction that was derived from the multidimensional hypothesis: They clearly show that FM is much more likely to produce a DL sequence associated with the wrong letter identity in response to a DL word than to a non-DL word.

ON THE DISTINCT STATUS OF DOUBLE-LETTER SEQUENCES

Thus far, we have been able to show that FM's impaired spelling performance confirms two major predictions of the multidimensional

hypothesis: That, under certain conditions of damage to graphemic representations, DL sequences should behave as units and that information about letter doubling may be preserved in spite of a loss of information about letter identities. These predictions directly follow from the central assumption that DL sequences are associated with a single grapheme token. FM's performance can thus be taken as further evidence in favor of that claim. However, one may still object to this conclusion by raising the possibility that there may be nothing unique about double letters. Although we have shown that their behavior clearly differs from the behavior of other adjacent letter pairs, which seems sufficient to reject the linear sequence hypothesis, it could still be argued that the data we presented thus far do not necessarily support the claim that double letters have a distinct status within orthographic representations. For example, one could propose that FM's performance may merely be constrained by the presence of a letter repetition in the target, whether involving adjacent letters or not. Or one could propose that double letters are special because they correspond to single phonemes in a word's grapheme-to-phoneme mapping. We will now evaluate each of these possibilities in turn.

Is the Behavior of Double-Letter Pairs Similar to the Behavior of Nonadjacent Repeated-Letter Pairs?

We tested the possibility that there may be nothing special about double letters per se by examining if pairs of nonadjacent repeated let-

TABLE 8
PROPORTIONS OF FM'S RESPONSES THAT INCLUDE A WRONG IDENTITY DOUBLE-LETTER PAIR FOR DOUBLE-LETTER WORDS VERSUS MATCHED CONTROLS

	Double-letter words	Controls	$\chi^2(1)=$
Spelling to dictation	.60 54/90	.16 14/90	37.8*
Written picture naming	.84 21/25	.04 1/25	32.5*
Delayed copy transcoding	.77 20/26	.08 2/26	25.5*

Note. Analysis include all responses in which one or both of the two critical letters of the target (e.g., rabbit, basket) does not appear any where in the response.

* $p < .001$.

ters (e.g., “cactus”; hereafter repeated-letter pairs) would result in the pattern of performance that was previously shown to be characteristic of DL pairs. That is, in order to determine if repeated-letter pairs would also behave as units, we undertook to determine if the probability of FM producing only one letter of a pair was lower for repeated-letter pairs than for otherwise comparable nonrepeated-letter pairs, as was shown to be the case for DL pairs versus non-DL pairs. We also examined the possibility that information about nonadjacent letter doubling may be preserved independently from information about letter identities by assessing the relative probability of FM’s responses to include a repeated-letter pair associated with the wrong letter identity for targets with and without a repeated letter (e.g., *patience* → *PATI-TOE* versus *mustache* → *MUSTALEA*). In addition, we examined the possibility that, by virtue of being similarly represented, DL pairs and repeated-letter pairs would be “interchangeable,” in the sense that more DL sequences would be produced in response to repeated-letter targets than to matched controls and vice-versa.

The controls for repeated-letter stimuli were chosen following the same procedure as before; that is, each word with a repeated-letter pair was matched to an arbitrarily chosen word of identical length that did not include a repeated letter (or a double letter) but that included a pair of letters with the same consonant/vowel status as the repeated letter pair in identical positions. These analyses were performed again on a subset of DL targets that did not include repeated-letter pairs (and matched controls with neither DL nor repeated-letter pairs) that were matched to the repeated-letter targets in terms of length. This precaution was taken in order to ensure that the previously reported results would replicate within this new subset of words of slightly different average length.

On the hypothesis that the behavior of DL sequences may simply reflect the effects of letter repetition, performance with repeated-letter pairs should differ from performance with their controls in the same way as performance with DL pairs differs from performance with their

controls. Also, one might expect that DL and repeated-letter pairs could be “interchangeable” in the sense that more DL pairs would be produced in response to repeated-letter targets than to matched control targets and conversely, that more repeated-letter pairs would be produced in response to DL targets than to matched control targets. In contrast, the multidimensional hypothesis predicts that performance with nonadjacent repeated-letter pairs should not show the same pattern as performance with DL pairs. Also, the two types of letter pairs should not be interchangeable. These expectations derive from the central assumption that the use of a single token to represent the identity of more than one letter of a word is limited to DL sequences. Therefore, if the specific behavior of DL sequences is really a consequence of their unique representational status, one would not expect any other kind of letter pairs to produce the same effects. In addition, the multidimensional hypothesis posits that the internal structure of words like “cactus” is identical to the structure of control words like “basket” which gives no reason to expect that these two types of words should result in different error patterns when their representations are damaged.

The results of this new set of analyses are presented in Tables 9 and 10. These results can be summarized as follows. First, FM’s data showed no evidence that repeated-letter pairs behaved as units (see Table 9): The probability of producing only one letter of a pair was equivalent for repeated-letter pairs and their controls [.36 versus .45 in spelling to dictation ($\chi^2(1) = 1.34, p > .10$), .54 versus .35 in written picture naming ($\chi^2(1) = 1.94, p > .10$), .26 versus .27 in delayed copy transcoding ($\chi^2(1) < 1.0, p > .10$)]. By contrast, the probability of producing only one letter of a DL pair was much lower than the probability of producing only one letter of its control [.17 versus .44 in spelling to dictation ($\chi^2(1) = 12.5, p < .001$), .11 versus .35 in written picture naming ($\chi^2(1) = 3.9, p < .05$), .05 versus .35 in delayed copy transcoding ($\chi^2(1) = 22.4, p < .001$)].

Second, there was no evidence that information about quantity can be preserved independently from information about grapheme iden-

TABLE 9

PROPORTIONS OF RESPONSES THAT INCLUDE ONE AND ONLY ONE LETTER OF A TARGET PAIR FOR DOUBLE-LETTER WORDS, REPEATED-LETTER WORDS, AND THEIR RESPECTIVE CONTROLS

	Spelling to dictation	Written picture naming	Delayed copy transcoding
Double-letter targets	.17	.11	.05
(e.g., rabbit)	13/75	3/26	4/81
Controls	.44	.35	.35
(e.g., basket)	33/75	9/26	28/81
Repeated-letter targets	.36	.54	.26
(e.g., cactus)	27/75	14/26	21/81
Controls	.45	.35	.27
(e.g., basket)	34/75	9/26	22/81

tities in the case of repeated-letter pairs (see Table 10): Whereas FM produced more erroneous DL sequences in response to DL targets than to control targets [26/39 versus 5/39 in spelling to dictation ($\chi^2(1) = 23.6, p < .001$), 7/11 versus 0/11 in written picture naming ($\chi^2(1) = 10.2, p < .01$), 11/13 versus 0/13 in delayed copy transcoding ($\chi^2(1) = 19.0, p < .001$)] as was previously shown on a larger subset of stimuli, he was no more likely to produce a repeated-letter pair in response to repeated-letter targets than to control targets (13/39 versus 16/39 in spelling to dictation, 3/11 versus 5/11 in written picture naming, 5/13 versus 7/13 in delayed copy transcoding).

Third, there was no indication that DL pairs and repeated-letter pairs are “interchangeable” (see Table 10): No more repeated letters were produced in response to DL targets than in re-

sponse to control targets (e.g., 8/39 versus 13/39 in spelling to dictation, all $\chi^2(1) < 1$) and, complementarily, there were no more double-letters produced in response to repeated-letter targets than to control targets (e.g., 4/39 versus 9/39 in spelling to dictation).

Taken together, these results unambiguously support the predictions of the multidimensional hypothesis regarding the expected behavior of DL pairs versus repeated-letter pairs. They therefore lend further support to the claim that DL pairs have a distinct status within graphemic representations that distinguishes them from other kinds of letter pairs.

These results can also be used to rule out another potential alternative explanation of the special behavior of DL sequences: That is, one may have argued that the reason why DL sequences behave as units is not because they are

TABLE 10

NUMBER OF ERRORS INVOLVING THE PRODUCTION OF AN ERRONEOUS DOUBLE-LETTER PAIR (DL) OR REPEATED-LETTER PAIR (RL) FOR DL TARGETS, RL TARGETS, AND THEIR RESPECTIVE CONTROLS

	Spelling to dictation		Written picture naming		Delayed copy transcoding	
	DL?	RL?	DL?	RL?	DL?	RL?
DL targets						
(e.g., rabbit)	26/39	8/39	7/11	2/11	11/13	4/13
Matched controls						
(e.g., basket)	5/39	13/39	0/11	3/11	0/13	2/13
RL targets						
(e.g., cactus)	4/39	13/39	0/11	3/11	0/13	5/13
Matched controls						
(e.g., basket)	9/39	16/39	1/11	5/11	0/13	7/13

Note. Analyses include all responses in which one or both of the critical letters did not appear anywhere in the response.

represented in a special way but rather because the patient may have difficulty accessing some specific letter identities. For example, FM may have much more difficulty producing the letter "B" than, say, the letter "R."⁶ Therefore, he might be expected to produce just one letter of the target sequence in a word like "carbon," to produce both of them in a word like "parrot" and to produce none in a word like "rabbit." Similarly, one could have tried to account for the preservation of doubling in cases of loss of information about the identity of the letter to be doubled by further assuming that letters that cannot be produced tend to be systematically replaced by some specific other letters; thus, if the letter "B" is hard to produce and tends to be replaced by the letter "L," one would expect errors such as rabbit → RALLIT. It is clear however that a difficulty in accessing specific letter identities cannot be an explanation for the special behavior of DL sequences, if only because it should affect repeated-letter pairs in a similar way, which is clearly not the case.

In addition, it may be worth noting that these results are problematic for earlier suggestions regarding the possible special status of repeated letters pairs in spelling. For example, Lecours (1966) argued, from his analysis of the spelling errors produced in the diary of Lee Harvey Oswald, that most cases of letter substitutions, omissions, additions, and transpositions involved repeated letters (whether adjacent or not). Also, Ellis (1979) reported, based on an analysis of a corpus of his own "slips of the pen," that virtually all occurrences of doublet-creating errors (e.g., these → THESSE) were associated with repeated-letter targets. His interpretation of this phenomenon seems to rely on the notion that all repeated letters, whether adjacent or not, are presented by a single letter identity token. It is unclear, however, that the data reported in these two papers really support the notion of a special status for repeated letters. This is because both studies failed to demon-

strate that the proportion of errors involving repeated letters was higher than would be expected with matched controls. The reported results may not be so surprising in light of the fact that most relatively long words—the very words usually most likely to be misspelled—include repeated letter pairs (see McCloskey et al., 1994, for a more extensive discussion of these two papers). Be this as it may, our own evaluation of the behavior of repeated-letter pairs certainly did not provide any support for the notion that they may have a distinct status. Neither did previous analyses of the performance of patients LB (Caramazza & Miceli, 1990) and HE (McCloskey et al., 1994).

Are Double Letters Special Because They Correspond to Single Phonemes?

Up to this point, all the evidence we have presented converges in favor of the claim that double-letter pairs have a distinct status within graphemic representations. However, one may challenge this interpretation by suggesting that FM's pattern of performance with double-letter sequences could instead derive from their special, although not unique, relationship with phonological word segments. That is, one may still want to ask whether or not the specific pattern of performance observed in relation to double-letter stimuli could be attributed to the fact that double letters, unlike some letter sequences (e.g., "SK" in BASKET) but just like some others (e.g., "CK" in ROCKET), represent a single phoneme in the corresponding phonological representation of words. Given this property of double-letter sequences in English, one may suggest that what FM preserves is information concerning the presence in a word of a letter cluster corresponding to a single phoneme (i.e., the presence of what we will call a digraph) rather than specific information about doubling independent of letter identity. If this were the case, words that include digraph sequences other than double letters (e.g., ROCKET) should produce the same pattern of performance as words with double letters.

We tested this possibility in the same way we tested the possibility that the double-letter effect may be a mere letter repetition effect. That is,

⁶ However, it should be noted that, apart from the advantage of vowels over consonants which was controlled for, there was no clear indication in the corpus that FM had more difficulty producing some specific letter identities than some others.

we asked the following questions: Is the probability of FM producing only one letter of a sequence lower for digraph pairs than for matched control pairs (i.e., do digraph sequences behave as units)? Is the probability of FM producing another digraph when he cannot produce the correct one (e.g., *rocket* → *ROPHET*) higher than the probability of producing a digraph in a control word (i.e., is there a preservation of information concerning the type of sequence to be produced independently from preservation of letter identity information)? Is the probability of producing a digraph in response to a DL target (e.g., *rabbit* → *RAPHIT*) higher than the probability of producing a digraph in response to a control word and, conversely, is the probability of producing a DL higher for digraph words (e.g., *rocket*→*ROBBET*) than for controls (i.e., are DL and digraphs “interchangeable”)? Here, as in the case of repeated-letter pairs, the prediction from the multidimensional hypothesis is that the answer to all these questions should be no.

The analyses we are about to present we carried out in exactly the same way as the previous ones. However, it should be pointed out that scoring the stimuli in terms of the presence or the absence of a digraph was not as straightforward as scoring them in terms of the presence or the absence of a double-letter pair or a repeated-letter pair. There were, on the one hand, some clear cases in which there either was a one-to-one correspondence between letters and phonemes (e.g., “basket”), in which case the stimulus would be scored as a no-digraph target, or else cases in which there was a pair of contiguous letters that clearly corresponded to a single sound (e.g., “rocket”), in which case the stimulus would be scored as a digraph target. On the other hand, there were a number of cases that were ambiguous either because (a) it was difficult to determine how many phonemes the target included (there was for example a problem with words including diphthongs, e.g., mouse, that some phonologists view as phonological units and others as composite sounds, or with words like “history” where it is not clear whether or not there is a phoneme between the

/t/ and the /r/) or because (b) some sounds were related to two discontinuous letters (as is mostly the case with words with a final “e,” e.g., “tame”), or for other similar reasons. Table 11 shows examples of words scored as having a digraph, no digraph, or scored as ambiguous; all ambiguous targets were removed from further analyses. We scored the responses as including a digraph whenever they included any sequence of letters identified as a digraph in the scoring of the targets, whether produced in a legal context or not (e.g., *QEATION*, *BUTHRE*). Note that some sequences, “ea” for example, function as digraphs in some words (e.g., “bear,” “pear”) but not in others (e.g., “real,” “idea”). However, we always scored such sequences as digraphs when they appeared in FM’s responses. The reason for that is that the vast majority of his responses were nonwords in the context of which it is not possible to determine how ambiguous sequences like “ea” should be pronounced (e.g., *APMEADON*, *AMMOREAT*).

The results of the different analyses that we performed are presented in Tables 12 and 13. It should be noted that the behavior of DL sequences was re-evaluated on a subset of words that were matched to Digraph words in terms of length.

The results of this new set of analyses can be summarized as follows. First, FM’s data showed no evidence that digraph pairs behaved as units (see Table 12): The probability of FM producing only one letter of a pair was not significantly different for digraph pairs versus their controls (.32 versus .47 in spelling to dictation, .35 versus .50 in written picture naming, .19

TABLE 11
EXAMPLES OF THE SCORING OF STIMULI IN TERMS OF THE
PRESENCE OR ABSENCE OF A DIGRAPH SEQUENCE

Stimuli scored as including a digraph	Stimuli scored as including no digraph	Stimuli scored as ambiguous and excluded
sock	bolt	town
brush	onion	table
beaver	cactus	flower
brother	pumpkin	history
bungalow	contract	question
artichoke	president	submarine

TABLE 12

PROPORTIONS OF RESPONSES THAT INCLUDE ONE AND ONLY ONE LETTER OF A TARGET SEQUENCE FOR DOUBLE-LETTER TARGETS, DIGRAPH TARGETS, AND THEIR RESPECTIVE CONTROLS

	Spelling to dictation	Written picture naming	Delayed copy transcoding
Double-letter targets	.07	0	.09
(e.g., rabbit)	5/68	0/20	7/78
Controls	.44	.60	.38
(e.g., basket)	30/68	12/20	30/78
Digraph targets	.32	.35	.19
(e.g., rocket)	22/68	7/20	15/78
Controls	.47	.50	.29
(e.g., basket)	32/68	10/20	23/78

versus .29 in delayed copy transcoding). By contrast, the probability of FM producing only one letter in DL pairs was much lower than for their controls [.07 versus .44 in spelling to dictation ($\chi^2(1) = 24.4, p < .001$), 0 versus .60 in written picture naming ($\chi^2(1) = 17.14, p < .001$), .09 versus .38 in delayed copy transcoding ($\chi^2(1) = 18.7, p < .001$)].

Second, there was no evidence that information about the presence of a digraph was preserved independently from information about letter identities (see Table 13): FM was no more likely to produce a digraph in response to a digraph target than to a control target (10/36 versus 12/36 in spelling to dictation, 4/9 versus 3/9 in written picture naming, 2/13 versus 2/13 in delayed copy transcoding).

Third, there was no indication that DL pairs and digraph pairs are “interchangeable” (see

Table 13): No more digraphs were produced in response to DL targets than in response to control targets (e.g., 12/36 versus 12/36 in spelling to dictation) or vice versa (e.g., 6/36 versus 6/36 in spelling to dictation).

Once more, the contrasting results obtained with digraph and DL pairs clearly support the claim that DL pairs have a unique status within graphemic representations. Nonetheless, it should be noted that there was a tendency for digraphs to behave as units in the sense that the probability of FM producing only one letter of a target sequence was lower for digraph targets than for their controls. Although this difference was not significant, it suggests that there may be something special about digraphs. However, this effect was of a much smaller magnitude than the one observed for DL pairs. Moreover, no similarity was observed between digraphs and

TABLE 13

NUMBER OF ERRORS INVOLVING THE PRODUCTION OF AN ERRONEOUS DOUBLE-LETTER PAIR (DL) OR AN ERRONEOUS DIGRAPH FOR DOUBLE-LETTER TARGETS, AND THEIR RESPECTIVE CONTROLS

	Spelling to dictation		Written picture naming		Delayed copy transcoding	
	DL?	Digraph?	DL?	Digraph?	DL?	Digraph?
Double-letter targets						
(e.g., rabbit)	19/36	12/36	7/9	3/9	9/13	0/13
Controls						
(e.g., basket)	5/36	12/36	1/9	2/9	1/13	4/13
Digraph targets						
(e.g., rocket)	6/36	10/36	1/9	4/9	1/13	2/13
Controls						
(e.g., basket)	6/36	12/36	1/9	3/9	0/13	2/13

Note. Analyses include all responses in which one or both of the critical letters did not appear anywhere in the response.

DL pairs in the two other analyses reported. Therefore, it seems highly unlikely that the pattern of performance associated with double letters is due to the fact that they are digraphs, that is, correspond to single phonemes.

CONCLUSION

The purpose of this study was to examine the claim that the word-level graphemic representations used in the course of spelling should be viewed as multidimensional mental structures rather than as ordered linear sequences of abstract letter identities. More specifically, we aimed at testing the claim that double-letter sequences have a special status within graphemic representations and that this specificity is best accounted for under the hypothesis that DL sequences are associated to a single grapheme token with quantity information being specified separately.

Our study revealed that different aspects of FM's impaired spelling performance support this view: (a) "splitting errors" (e.g., *basket* → *BASTEK*) occurred less frequently on words with double letters than on otherwise comparable words without double letters, (b) errors involving the production of only one letter of a target pair (e.g., *basket* → *BAKET*, *rabbit* → *RABIT*) occurred less frequently on words with double letters than on words without double letters, (c) errors involving the production of an erroneous double letter (e.g., *basket* → *BAPPET*; *rabbit* → *RAPPIT*) occurred more frequently on words with double letters than on words without double letters. These results indicate that (a) double letters behave as units, and (b) information about grapheme quantity (i.e., information about doubling) can be preserved independently from information about grapheme identity.

In addition, we showed that this particular pattern of performance was specific to double letter pairs and did not apply to other types of letter pairs that shared some surface characteristics with double letter sequences, namely repeated letter (e.g., *cactus*) pairs and digraphs (e.g., *rocket*). More specifically, we showed that (a) errors involving the production of only one letter of a target pair did not occur less

frequently on words with repeated letters or digraphs than on control words without repeated letters or digraphs, and (b) errors involving the production of an erroneous repeated letter did not occur more frequently on words with repeated letters than on words without repeated letters, just as errors involving the production of an erroneous digraph did not occur more frequently on words with digraphs than on words without digraphs. Furthermore, we also showed that there were no more repeated letters or digraphs produced in response to words with double letters than to words without double letters and, complementarily, that no more double letters were produced in response to words with repeated letters or digraphs than to words without repeated letters or digraphs.

Interestingly, FM's pattern of performance also seemed to indicate that his knowledge of the formal properties of graphemic representations was not limited to knowing whether a particular target contained a double-letter pair. For example, double consonants virtually never occur at the beginning of words in English and FM never produced any. Note that FM's honoring of this orthographic constraint cannot merely be explained by the fact that he makes fewer errors in word-initial positions or by assuming that he generally avoids producing sequences that do not occur in English: FM did in fact produce 17 errors in which the first two letters produced never occur in that sequence in English (e.g., *trip* → *TPIR*, *crime* → *CMINE*, *question* → *QAETION*). In addition, FM also seemed to have well-preserved knowledge of which particular letters can or cannot be doubled. Out of the 104 double-letter substitutions that he produced, only three involved a letter that is never or hardly ever doubled in English (*squirrel* → *SIQQIN*, *barrel* → *BAWWOL*, *arrow* → *AWWO*).

Taken together, FM's results clearly demonstrate that double-letter sequences have a special status within graphemic representations; therefore, these representations cannot merely consist of a linear sequence of graphemes. Rather, our results support the view that graphemic representations are multidimensional mental structures that comprise at least two separate

dimensions: One specifying grapheme identities and another specifying grapheme quantity, or doubling (Caramazza & Miceli, 1990). As noted in the introduction, one implication of this hypothesis is that brain damage may selectively affect each of these two kinds of knowledge. In support of this view, Miceli et al. (1995) and Venneri and Cubelli (1993) have recently reported patients who show selective difficulties in processing the doubling feature in graphemic representations. Their patients frequently omitted one of the letters in DL pairs but not letters in other letter clusters or digraphs. It would seem, then, that there is fairly compelling evidence for the hypothesis that graphemic representations are multidimensional objects and not simply linear sequences of abstract letter identities.

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