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The Organization of Letter-Form Representations in Written Spelling: Evidence from Acquired Dysgraphia

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We report on an Italian brain-damaged patient with impaired written spelling. The patient's errors, in different fonts and scripts, consist mainly of letter substitutions (e.g., *filo* [thread] → *T*ILO). The results of various tests indicate that letter substitution errors arise because of a deficit in accessing the letter-form representations supporting written spelling. Letter substitutions occurred predominantly between letters with common strokes (e.g., *C* and *G; b* and *p*). Similarities in terms of global letter shape or letter sound were not valid predictors of letter substitution errors. Letter frequency, consonant–vowel status, and letter gemination were factors affecting letter substitution errors. The results of our investigation suggest that information about letter strokes are stored at the level of letter-form representations, and that access to these representations is sensitive to letter frequency. The results further indicate that letter-form representations do not specify whether a letter is a consonant or a vowel, or is a geminate.

A few studies have recently documented brain-damaged patients with spelling impairments consisting primarily of letter substitution errors (Black, Behrmann, Bass, & Hacker, 1989; Del Grosso Destrieri et al., 2000; Lambert, Viader, Eustache, & Morin, 1994; Rapp & Caramazza, 1997; Zesiger, Martoty, & Mayer, 1997; Zesiger, Pegna, & Rilliet, 1994). Examples of their errors may include *gentle* → *C*ENTLE, where the letter *g* is replaced by the letter *C;* and *house* → *E*OUSE, where the letter *h* is replaced by the letter *E* (examples from Black et al., 1989). These errors occurred predominantly, if not exclusively, in written spelling—patients' performance in oral spelling was far superior, if not completely intact. Their handwriting was perfectly legible, and letters were printed accurately. Notably, their substitutions were not uniformly distributed across letters; rather they tended to involve letters that are visually similar.

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For example, with capital case letters, substitutions were typically observed with pairs such as *B-P, C-G,* and *M-N.* The fact that errors were confined to handwriting, along with the fact that letters were accurately formed, severely constrains hypotheses about the source of patients' substitutions. If we take as reference the general model of spelling presented in Fig. 1 (after Ellis, 1982; Goodman & Caramazza, 1986; Margolin, 1984), we can rule out that their substitutions arose because of deficits located at any level preceding and including the graphemic buffer. Up to this level, processes supporting the retrieval of stored orthographic knowledge, a direct phoneme-to-grapheme translation, and the temporary holding of information about word

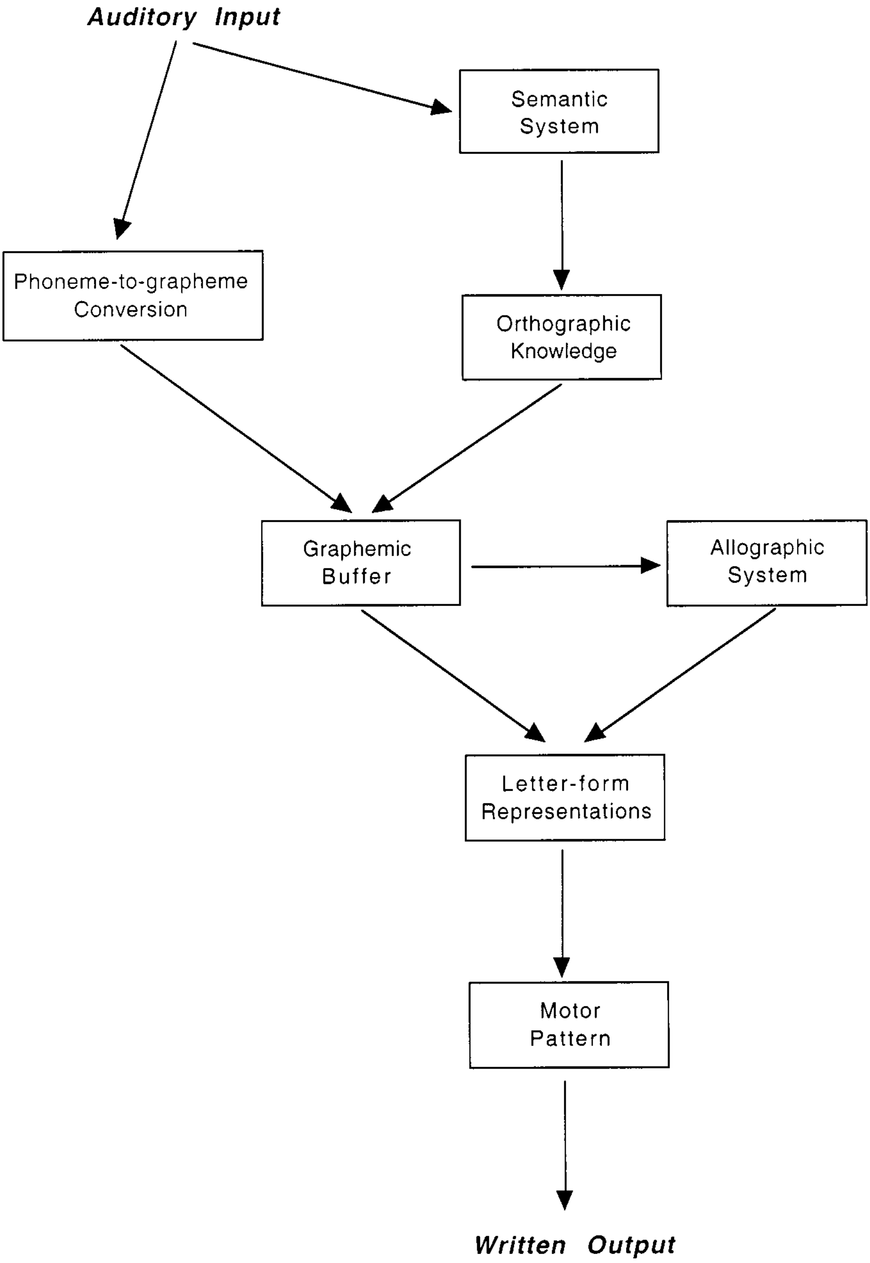


FIG. 1. Schematic model of the spelling system.

orthographic content are also needed for oral spelling. A deficit at any of these levels would lead to an impaired performance in oral spelling. Evidence that patients' oral spelling is (relatively) preserved would exclude a deficit at each of these levels as the principal cause of their letter substitutions. Moreover, patients' ability of selecting the appropriate font suggests a preserved access to the allographic system, devoted to specifying letter font (upper vs lower) and letter script (print vs cursive) (on this point see, e.g., De Bastiani & Barry, 1989; Patterson & Wing, 1989). Finally, the presence of well-formed letters would demonstrate the sparing of the motor movements involved in handwriting. By logic of exclusion, the deficit responsible for the substitutions of visually similar letters seems to be located at the level of letter forms, the representations specifying the shape taken by letters in a given font or script (e.g., A vs a vs *a*).

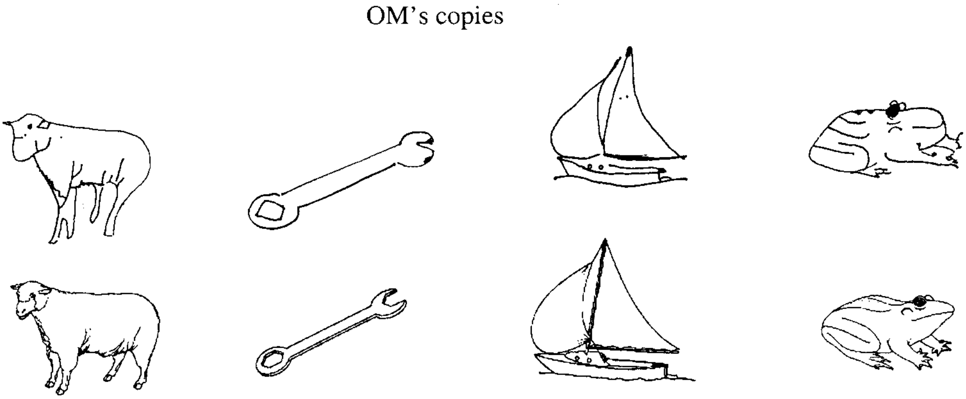
The importance of the spelling impairment described above for spelling models is twofold. On one hand, it demonstrates that a distinct level of processing exists for letter forms. On the other hand, the evidence that substitutions occurred mainly between physically similar letters provides the basis for drawing inferences about the organization of the letter-form representations accessed in written spelling. Such error distribution is compatible with at least two distinct proposals. One possibility is that letter-form representations specify the visuospatial characteristics of the whole letter. On this view, stored letter representations are functionally equivalent to templates, and these templates guide specific motor patterns. Physically similar letters can be thought of as being closer in a representational space than physically different letters. Following brain damage, it could be difficult to access letter-form representations, and in these circumstances, discrimination between similar letters would be particularly problematic. Alternatively, it could be proposed that letter-form representations encode information about a letter's strokes—their number, direction, and orientation, and their initial and terminal points. Information about letter strokes is transformed into precise motor commands. Stroke information is abstract in the sense that it does not encode features like size or letter orientation—these features are specified at more peripheral levels of processing. Letters having common strokes are more confusable, and this explains why, in conditions of brain damage, exchanges tend to occur primarily between letters sharing strokes.

There is some evidence in favor of the latter alternative. For example, Rapp and Caramazza (1997) considered two empirical measures of letter similarity, one reflecting similarity in terms of letter global shape, the other in terms of shared strokes. They then obtained two distinct sets of letter pairs, one composed of letters of similar shape, the other of stroke-similar letters. Crucially, Rapp and Caramazza observed that patients' letter substitutions were significantly more frequent among stroke-related letter pairs, a result suggesting that the letter-form representations accessed in written spelling specify information about the strokes—number, direction, orientation—composing each letter (for a similar analysis see also Zesiger et al., 1994). Additional evidence pointing to a stroke-based representation was found in two dysgraphic patients documented by Del Grosso Destreri et al. (2000) and by Lambert et al. (1994), respectively. The probability of observing a letter substitution error was linearly related to the number of shared strokes: more errors were found for letter pairs having common strokes. Remarkable evidence was then provided by patient HP, documented by Zesiger et al. (1997), who, in lowercase print, exchanged only the letter pairs *b*-*p* and *d*-*q*, revealing a selective confusion between down- and upward strokes.

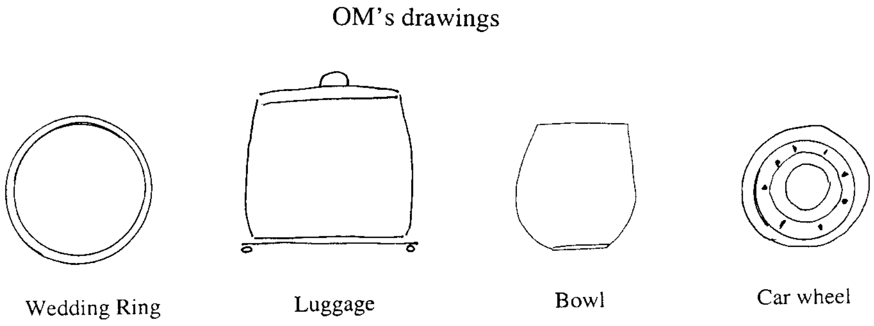
Here we present a new case of a brain-damaged patient (OM) with impaired handwritten spelling and seemingly intact oral spelling, whose errors consist predominantly of letter substitutions between physically similar letters. A detailed investigation of OM’s deficit indicates that his letter substitutions were caused by a damage at the level of letter-form representations. Unlike previous studies, which examined print and prevalently uppercase letters, we collected a large corpus of letter substitutions both in print *and* in cursive, and in upper- *and* in lowercase fonts. Various analyses were directed at testing the hypothesis that stroke similarity underlies OM’s letter substitutions. We also attempted to determine whether a variety of other factors—including letter frequency, letter sound, and consonant/vowel status—contributed to OM’s letter substitutions. By isolating the factors affecting OM’s letter substitutions, it was possible to elucidate various aspects of the organization of letter-form representations.

CASE REPORT

OM is an Italian-speaking, right-handed male with 13 years of education. When he was 36 years old, he suffered carbon monoxide poisoning. Prior to the poisoning, he worked as an engine designer. The current study was carried out 8 years after the poisoning. An MRI done at this time revealed a bilateral lesion in the region of the globus pallidus, and a bilateral lesion of the occipital–parietal–temporal carrefour. At the time of the current study, OM presented with the following neuropsychological profile. He had a visual recognition deficit for pictured objects, faces, and facial emotions. He correctly named 61% of the pictures in the Snodgrass and Vanderwart (1980) set ($N = 260$; mean accuracy of 10 control subjects matched for age and eduction: 97%, $z = -23$). Naming errors consisted mainly of semantically related names (e.g., *horse* → ‘‘donkey;’’ *crocodile* → ‘‘animal;’’ 48%) and ‘‘don’t know’’ responses (42%). OM’s remarkable ability to copy drawings (see Fig. 2) suggests



OM’s copies



OM’s drawings

FIG. 2. OM’s copies and drawings. The almost perfect circles were drawn without the aid of a device.

general preservation of early visual processing. Objects presented in modalities other than visual were correctly named. For example, OM was 95% accurate in naming objects described in oral definitions (controls' accuracy: 96%). He had no signs of neglect. The visual field was normal. Performance was within the normal range on Raven Progressive Colored Matrices (34/36). The patient was not aphasic as assessed by the Aphasia Examination Test (Basso, Capitani, & Vignolo, 1979). The results of the dyslexia test (Sartori, 1984) were consistent with the clinical profile of phonological dyslexia. Single letter reading was intact. Asked to form a mental image of a letter and to judge whether it contains a straight or a curved stroke (Kosslyn, 1980), OM always responded correctly. OM presented with severe anterograde amnesia. Digit span and Corsi span were within the normal range. Oral and limb apraxia were absent (De Renzi, Motti, & Nichelli, 1980). OM's drawings (both from memory and from copy; see Fig. 2) are dexterous and reflect his professional skills as a designer.

In a written picture-naming task, we noted that OM produced spelling errors, typically letter substitutions or errors denoting a lack of orthographic knowledge. This observation prompted the detailed investigation of OM's spelling. The investigation lasted 6 months, and during this time his condition remained stable.

OM's Spelling

Uppercase Writing

OM wrote words in print and uppercase font in two tasks: spelling-to-dictation and written picture-naming. In the first task, he wrote 17,457 Italian words of various length (between 3 and 17 letters) and of different grammatical categories. The experimenter read the words one at a time; OM repeated the word aloud and then wrote it. Word repetition ensured that the patient understood the target word. Whenever the patient failed to repeat a word, the experimenter presented it again, although this seldom occurred. The words were presented in lists of approximately 400 stimuli, and each list was administered in a different testing session. In the written picture-naming task, OM was shown 160 pictures and was instructed to name the depicted object and its parts. He printed a total of 889 words, lengths ranging from 3 to 14 letters.

The experimenter recorded the mistakes and corrections of OM's writing. We always scored the patient's first response. Making spelling errors was particularly frustrating for OM, and whenever he realized that he had committed one, he scratched out the word and started to write it from the beginning. As a result, we collected a few word fragments containing errors—these errors were also included in the analyses. Due to his visual recognition deficit, OM occasionally named a pictured object incorrectly. We only noticed visually related errors (*drum* → SCATOLA [box]), or visually and semantically related errors (*duck* → GALLO [rooster]). Because we were interested in spelling errors, we did not make any distinction between correct and incorrect naming responses.

OM wrote with his dominant right hand, and his writing was perfectly legible, as is apparent in samples shown in Fig. 3. A comparison with premorbid writing samples did not reveal any noticeable change in his calligraphy. The spelling errors were grouped into three major categories, each involving a different level of analysis: words, graphemes, and strokes.

Word errors. This category contains errors reflecting the unavailability of stored orthographic knowledge. Because of the high degree of phoneme-to-grapheme consistency present in Italian, word errors can be observed with a handful of phonological segments, namely segments that can be mapped onto distinct graphemic sequences

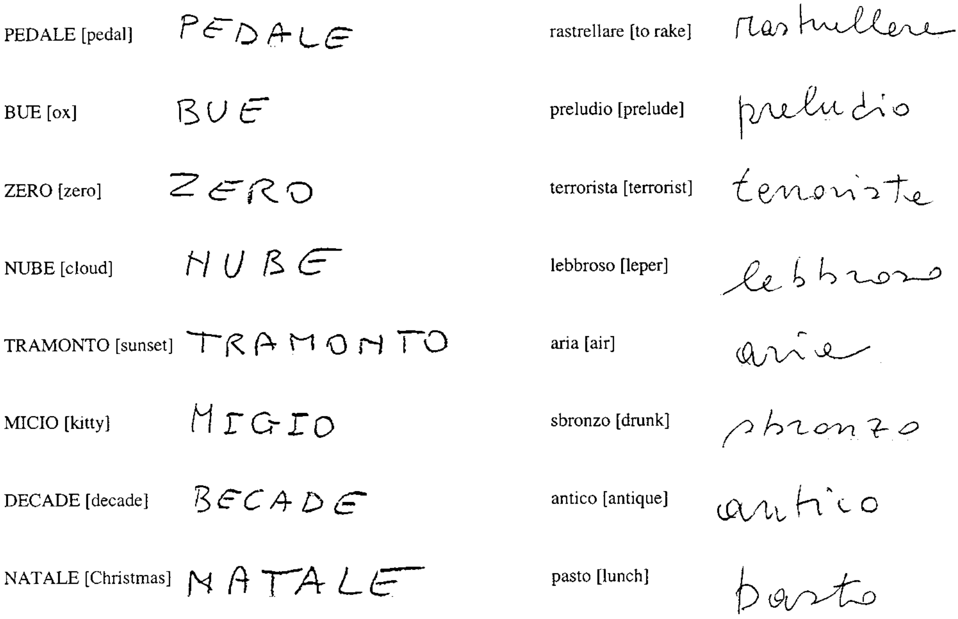


FIG. 3. Samples of OM's writing. Notice the letter substitutions: *micio* → MI*G*IO, *decade* → *B*ECADE, *natale* → *M*ATALE, and *pasto* → *b*asto.

(i.e., /kw/, /tʃe/, /li/, and /dʒe/). For example, the phonemes /kw/are realized as *cu* (like in *cuoco* [cook]) or *qu* (like in *quota* [quota]). In errors like *cuoco* → QUOCO, target and response sound identically; these errors indicate that the patient's spelling relied on phoneme-to-grapheme procedures, rather than on stored orthographic knowledge. Errors of this sort were scored as *phonologically plausible errors.* In Italian, a stress mark indicates that the main stress falls on a word's final vowel (e.g., *però* [however], *città* [city], *difficoltà* [difficulty]). Because there are words whose stressed final vowel is not overtly marked (e.g., *qui* [here]), stress mark must be a feature stored lexically. Errors involving the deletion or the incorrect addition of stress marks were listed as stress errors.

Grapheme errors. This category includes errors that involved (a) the substitution of a grapheme (e.g., *micio* → [kitty] MI*G*IO); (b) the deletion of one or more graphemes (e.g., *piedi* → [feet] PIDI); (c) the incorrect insertion of one or more graphemes (e.g., *polizia* [police] → POLIZZIA); (d) the transposition of two graphemes within the word (*stereotipo* [stereotype] → STEREO*PIT*O).[1]

Stroke errors. Grouped here were errors in which the addition, omission, or substitution of a letter stroke resulted in a nonexisting letter. Occasionally, the patient omitted the space between adjacent letters and fused them together. For example, in writing the letters *N* and *E,* he added three horizontal strokes to the vertical stroke of the *N.* Errors of this kind were also scored as stroke errors.

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[1] The scoring of grapheme errors that occurred in word fragments presents some problems. For example, in the error *tonalità* [tonality] → TONALL, has the second L to be scored as letter addition or letter substitution? Or does the error *turista* [tourist] → TURIT count as a deletion or a substitution? These ambiguous errors were scored consistently to the error patterns observed with completed words (see next section). Thus, errors like *tonalità* → TONALL, where letters were duplicated, have been scored as additions, and errors like *turista* → TURIT, where letters were anticipated, have been scored as deletions.

Results and error analysis. The percentage of incorrectly spelled words was equal to 12.8% (2237/17,457) in the writing-to-dictation task, and to 13.8% (123/889) in the written picture-naming task. Because responses were qualitatively and quantitatively similar in the two tasks, we analyzed them together. We scored a total of 2401 errors, and their distribution across the various error types is shown in Table 1. Two points are worth stressing. First, OM produced errors of various sorts. Second, substitutions (e.g., filo [thread] → *T*ILO) were the errors most commonly found in the corpus (72.8%). Next, we present a detailed analysis of the errors that OM produced in writing uppercase words.

Word errors. Phonologically plausible errors were found principally with the phonemes/ku/(e.g., *frequente* [frequent] → FRE*C*UENTE; 137/162, 84.5%). Despite the numerous opportunities to produce phonological errors with other phonological segments (e.g.,/tʃe/, /dʒe/), such errors were observed far less frequently. Semantic errors were confined in the written picture-naming task, as expected given his visual recognition deficit.

Grapheme errors. Substitutions (e.g., *filo* [thread] → *T*ILO) were the most frequent errors in the corpus (72.8%; $N = 1747$). These errors were not lexically constrained. In fact, seldom did the grapheme change result in a real word (e.g., *frutto* [fruit] → F*L*UTTO [wave]; 17/1747, 0.9%). Frequently, however, substitutions ended in strings violating the graphotactic constraints of the language (e.g., *schienale* [back] → SC*N*IENALE). In a few cases, substitutions were due to the repetition of an adjacent grapheme (e.g., *scrivere* [to write] → S*S*RIVERE; $N = 14/1747$, 0.8%), or its anticipation (e.g., *fornire* [to provide] → FO*N*NIRE; $N = 26/1747$, 1.4%).

The second most frequent errors in the corpus were deletions (11.3%; $N = 272$). With the exception of one error (*intransitabilità* [intransitability] → INTRANSIBILITÀ), single graphemes were omitted. In only two cases did a deletion lead to an existing word (*sedile* [seat] →SEDIE [chairs]; *prelato* [prelate] → RELATO [related]). Deletions were proportionally more common for consonants (242/272; 89.0%) than vowels (30/272; 11.0%). This asymmetry is in part explained by the

TABLE 1

Distribution of OM's Errors—Words Printed with Uppercase Letters in Writing-to-Dictation and Written Picture-Naming Tasks

Error type	*N*	%
Word errors		
Phonologically plausible errors	162	6.7
Stress errors	15	0.6
Total	177	7.3
Grapheme errors		
Substitutions	1747	72.8
Deletions	272	11.3
Insertions	109	4.6
Transpositions	7	0.3
Total	2135	89.0
Stroke errors		
Stroke deletions	53	2.2
Stroke additions	18	0.7
Wrong stroke	1	0.1
Letter fusion	17	0.7
Total	89	3.7
Total	2401	100

occurrence of two types of deletion errors selectively involving consonants—the deletion of geminate letters and the deletion of the letter *c*. In Italian, essentially only consonants can be geminate (the few cases of vowel geminate are borrowings from foreign languages; e.g., *zoo* [zoo]). Deletions of a geminate consonant (e.g., *bocca* → [mouth] BOCA) were observed 127 times, and accounted for 46.7% of the deletions.[2] Furthermore, 26.4% of the deletions (72/272) were found in the graphemic cluster *sc* (e.g., *scintilla* [spark] → SINTILLA). In Italian, the *sc* cluster corresponds to the phoneme /ʃ/, as in *scena* [scene] and *fascia* [bandage], or to the phonemes /sk/, as in *scoglio* [cliff] and *scambio* [exchange]. Interestingly, OM's deletions appeared almost exclusively (66/72; 91.7%) in *sc* clusters realizing the phoneme /ʃ/. These deletion errors do not seem to reflect a more general problem with phonemes realized by grapheme clusters. Italian orthography presents with several clusters of this sort, including *gl* → /ʎ/ (e.g., *foglia* [leaf]), *gn* → /ɲ/ (e.g., *gnomo* [gnome]), *ch* → /k/ (e.g., *chiodo* [nail]), and *gh* → /g/ (e.g., *cinghia* [belt]). The incidence of deletion errors was far lower for these clusters (between 0.7 and 3.6%) than for *sc* clusters (20.8%). A closer scrutiny revealed that omissions occurring in *sc* clusters predominantly involved the grapheme *c* (57/72, 79.1%). What can account for this disproportion? We suspect that it reflects OM's approach to spelling, and a particular feature of his dialect (Venetian), in which the phoneme /ʃ/ is often pronounced as /s/. If words like *fascia* or *scena* are pronounced /fasia/ and /sena/, and the patient relied on phoneme-to-grapheme conversion mechanisms, he would transcribe these words omitting the letter *c*, as FASIA and SENA. An analogous explanation might also account for the deletions observed with geminate letters. Geminate deletion is another feature of the Italian dialect spoken in the patient's region.

Insertions represented 4.6% of all errors (109/2401), and with one exception (e.g., *registro* [register] → REGISTR*TR*O) were due to the addition of a single grapheme. Insertions did not yield existing words, except in one case (*antenato* [ancestor] → ANTEN*N*ATO [with antennas]). In the majority of cases (96/109, 88.1%), insertions were due to the duplication of a letter, as, for example, in *polizia* [police] → POLIZ*Z*IA. Few insertions resulted in violations of graphotactic rules of Italian (an example was *schermo* [screen] → SCHERM*M*O).

Stroke errors. On 89 instances OM produced a nonexisting letter. This occurred because a stroke was omitted (53/89; 59.6%) or added (36/89; 20.2%), and not because a stroke was substituted by another stroke—this occurred in only one instance (with the mirror-reversed letter N). Also, in 17 cases, OM fused two letters together.

It seems almost the rule that dysgraphic patients produce a variety of errors, and OM is no exception. Very likely, some of his errors reflect a deficit in accessing stored orthographic knowledge. This holds for phonologically plausible errors, for errors with stress mark, and for letters deletions involving geminate letters and *sc* clusters. All these errors resulted in letter strings sounding like existing words (occasionally, existing dialectal forms), and were obtained by applying phoneme-to-grapheme conversion rules. A deficit in accessing stored orthographic knowledge cannot account for the other errors produced by OM (letter substitutions and additions, and stroke errors). The remaining of the investigation focuses on substitutions and the first objective is to define the causes of these errors. The functional damage underlying substitutions is probably different from the one responsible for additions and deletions—however, defining the causes of the letter errors goes beyond the aims of the present paper.

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[2] In the whole corpus, there were 8034 geminate letters. OM omitted a geminate letter only 1.6% of the times.

TABLE 2
OM's Errors in the Oral Spelling Task

Target		Error
Letter substitutions		
Bolgi*a*	[mess]	b-o-l-g-i-*o*
Br*u*sco	[rough]	b-r-*o*-s-c-o
Pomic*e*	[pumice]	p-o-m-i-c-*o*
Nom*a*de	[nomad]	n-o-m-*e*-d-e
Ulc*e*ra	[ulcer]	u-l-c-*i*-r-a
Letter deletions		
Abd*i*ca	[abdicates]	a-b-d-c-a
Chi*u*se	[closed]	c-h-i-s-e

Oral Spelling

There is the possibility, suggested, for example, by the appearance of phonologically plausible errors, that OM has impaired access to orthographic knowledge. For spelling a word, he had then to rely on sublexical mechanisms. A deficit of these mechanisms could lead to substitution errors. Another possibility is that substitutions arose from a deficit at the level of the graphemic buffer. Substitutions are indeed found in dysgraphic patients with selective damage to the graphemic buffer (see e.g., Caramazza, Miceli, Villa, & Romani, 1987; Jonsdottir, Shallice, & Wise, 1996; Katz, 1991; McCloskey, Badecker, Goodman-Schulman, & Alimosa, 1994). Both accounts make an identical prediction: substitutions should also be observed in the oral spelling task. For oral spelling, OM would rely on sublexical mechanisms, and oral spelling also requires holding information in the graphemic buffer. Therefore, a damage to sublexical mechanisms, or to the graphemic buffer, would lead OM to produce substitutions. However, if the substitutions observed in the written spelling task were caused by damaged letter-form representations, we do not anticipate an impaired performance in the oral spelling task.

A caveat should be considered here. As noted in any study of spelling carried out in Italian, oral spelling is essentially foreign[3] to Italian speakers; because of the near absolute transparency of the language, they do not normally perform this task. Very likely, even neurologically intact speakers would not perform errorlessly in the oral spelling task. In consideration of this, it is perhaps more informative to compare OM's performance in oral spelling and writing-to-dictation tasks, rather than examining whether, in the oral spelling task, the patient committed any errors.

Given the limitations that Italian speakers could experience in oral spelling, we included only relatively short words (six letters, $N = 100$). Moreover, because oral spelling was meant to test the intactness of nonlexical spelling mechanisms, all words had a transparent orthography. The experimenter named the words one at a time. We analyzed the patient's first responses. We recorded seven errors: all were grapheme errors (substitutions and deletions; see Table 2). For six letter words, the proportion of incorrectly spelled letters was greater in the writing-to-dictation than in the oral spelling task (7.4 vs 1.1%; *McNemar* test, $p < .01$). In both tasks, substitutions were the prevailing errors, although they differed in one crucial respect: in oral spelling, substitutions were found with vowels (e.g., ulc*e*ra → ''u-l-c-*i*-r-a''), whereas in writing-to-dictation they occurred almost exclusively (96%) with consonants.

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[3] The evidence showing this point most convincingly is perhaps that Italian speakers claim not to have an Italian word for oral spelling—indeed there is a term (*compitazione*), but few seem to know of its existence.

OM's performance differed sharply between written and oral spelling tasks, quantitatively and qualitatively. This rules out the hypothesis that mechanisms common to both tasks are responsible for the overwhelming incidence of substitutions in written spelling. We believe that the few errors encountered in the oral spelling reflect his total lack of familiarity with this task. By further inference, it can be concluded that the grapheme buffer and grapheme-to-phoneme mechanisms are intact. Additional evidence demonstrating the intactness of the graphemic buffer is provided by the following analysis of the length effect in written spelling.

Length Effect

The presence of a length effect is one of the major characteristics of a graphemic buffer deficit: errors tend to increase as a function of word length, and they tend to occur more frequently at the end rather than at the beginning of the word (see e.g., Miceli, Silveri, & Caramazza, 1987; Nolan & Caramazza, 1983). Consistent with the results of the oral spelling task, which rule out a graphemic buffer deficit, we expect not to find an effect of word length in the substitutions observed in the writing-to-dictation task. Figure 4 shows the probability of encountering a substitution error as a function of the number of letters in the target word (range 4–13 letters). Error probability remained unaffected by word length (Pearson $r < .1$, NS). We also examined whether substitutions occurred more frequently in the initial vs the final part of the word. Because in written spelling substitutions were more common with consonants, and because in Italian consonants rarely occurred in word final position, we contrasted the probability of encountering substitutions in initial vs penultimate word positions. The results are inconsistent with the hypothesis of a graphemic buffer deficit—if anything, error probability tended to be greater in the initial than in the final part of the word (1.9% vs 0.9%; data collapsed for words of length 4–13 letters).

The analyses of length effect, along with the results of the oral spelling task, rule out the hypothesis of a graphemic buffer deficit. The results of the oral spelling task are also incompatible with the hypothesis of impaired grapheme-to-phoneme conver-

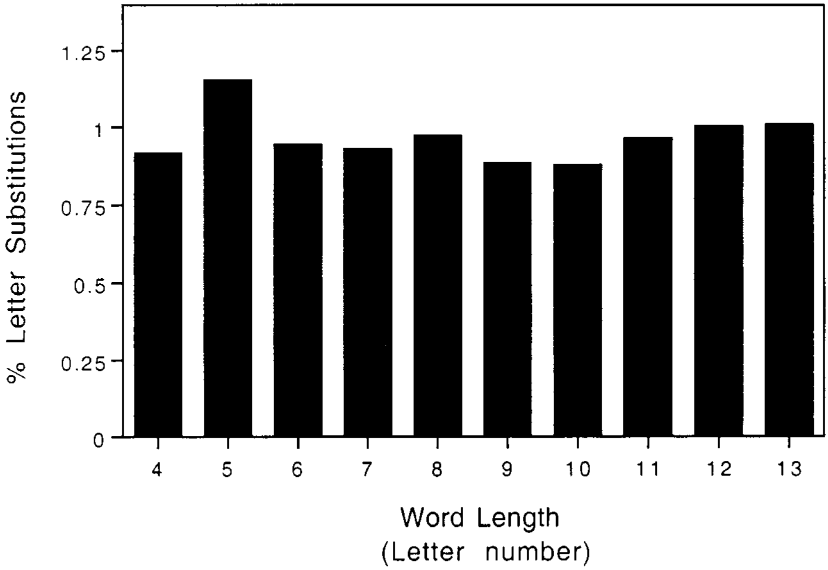

FIG. 4. OM's percentage of letter substitutions as a function of word length (number of letters) observed in written spelling tasks (print and uppercase letters).

TABLE 3

Number and Percentage of OM's Substitutions across the 21 Letters of the Italian Alphabet Written in Print and Uppercase Font

	Letter substitution errors	
Letter	*N*	%
B	172	5.85
M	215	5.07
G	196	4.81
F	105	3.79
N	367	3.33
Q	4	1.74
Z	57	1.58
P	90	1.50
D	55	1.48
C	136	1.36
T	119	0.76
H	6	0.75
L	40	0.48
R	81	0.46
V	9	0.38
I	44	0.21
S	22	0.21
U	4	0.10
E	12	0.05
O	7	0.04
A	6	0.03

sion mechanisms. If we consider that OM is able to print well-formed letters, and that he did not have problems in selecting letters in a given script (print vs cursive) or case (upper vs lower), then we can also rule out a deficit at the level of the allographic system and at the level of the motor programs implicated in writing. By logic of exclusion, and in reference to the spelling model depicted in Fig. 1, we hypothesize that OM's substitutions originate from a deficit at the level of letter-from representation. The signature of a deficit at this level is that substitutions involve physically similar letters. Whether OM's substitutions also exhibit this feature is examined in detail in the following sections.

Substitution Errors

Table 3 shows the percentage of substitutions observed for each uppercase letter. There are two points to be made here. First, errors were unequally distributed across the 21 letters of the Italian alphabet—they tended to occur more frequently with some letters (e.g., *B*, *G*, and *M*) rather than others (e.g., *A*, *S*, and *H*). Second, errors were more numerous with consonants (mean = 2.09%; range 0.21–5.85%) than vowels (mean = 0.08%; range 0.03–0.21%). Additional important information about the nature of substitutions can be garnered from an inspection of the confusion matrix[4]

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[4] Data corresponding to the pairs *U-V* and *V-U* are not reported, because these letters were often printed identically. Furthermore, the error probability for the letter *T* was calculated excluding geminate *T*s, because geminate and nongeminate *T*s were printed differently.

shown in Table 4. Substitutions appear in only 65% of the matrix cells, and concentrate on a few cells. Thus, the substitutions involving four letter pairs (*B-P*, *C-G*, *F-T*, and *M-N*) account for 63.2% of the errors.

The most striking feature of OM's substitutions is not only that they are unevenly distributed among letters, but also that they tend to concentrate on a few letter pairs. At a first glance, substitutions seem confined to physically similar letters, such as *B* and *P*, or *C* and *G*. That is, letter physical similarity seems to be determining the error distribution observed in OM. However, one might contend that letters similar in sound tend to participate in the substitution errors, and point out that errors were especially numerous with pairs of phonologically close letters, like *B-P* or *M-N*. On this view, errors are more a matter of phonological rather than visual similarity. What is the strength of this view? Can it provide a reasonable account of OM's substitutions? There are three lines of evidence relevant here, and taken altogether make the hypothesis of phonological similarity untenable.

When presented over a noisy channel, some phonemes are recognized better than others (Miller & Nicely, 1955; Singh, 1966), and error probabilities in phoneme recognition provide an indirect estimate of phoneme similarity. If phoneme similarity influences OM's letter substitutions, we should find a positive correlation between the error probabilities observed in OM's spelling and in phoneme perception. Data about the confusability of Italian consonants have been reported by Magno-Caldognetto, Ferrero, and Vagges (1983). In their study, consonants were presented along with the vowel /a/, and in conditions varying for signal-to-noise ratio (20, 15, 10, 5, 0, −5 dB); for each of the 21 Italian consonant phonemes, an overall error probability was obtained by averaging the probability found across conditions. We then determined OM's probability of substituting each consonant phoneme. The correlation between incorrect phoneme recognition and OM's substitutions was not significant ($r = -26$), a finding problematic for the hypothesis that OM's substitutions are affected by phonological similarity. Other, more subtle evidence appeared when we consider the letters *C* and *G*. In Italian, they realize multiple phonemes—/k/ and /tʃ/ for the letter *C*, and /g/, /dʒ/, /ɲ/ and /ʎ/ for the letter *G*. Of these phonemes, /k/ and /g/, and /tʃ/ and /dʒ/ are identical for place of articulation and manner, and thus constitute minimal pairs (Nespor, 1993). If phonological similarity is critical, $G \rightarrow C$ errors should prevalently occur when the letter *G* corresponds to the phonemes /g/ (as in *gala* [gala]) and /dʒ/ (as in *regione* [region]), not when it corresponds to the phonemes /ɲ/ (as in *ragno* [spider] and /ʎ/ (as in *aglio* [garlic]). In reality, $G \rightarrow C$ substitutions were equally probable when the letter *G* realized the phonemes /g/ and /dʒ/ (137/3605, 3.8%), or the phonemes /ɲ/ and /ʎ/ (28/633, 4.4%). Another line of evidence problematic for the phonological similarity account arises when we consider how phonology would affect OM's spelling. Our data demonstrated that OM's access to orthographic knowledge was impaired, and that his written spelling was supported by phoneme-to-grapheme conversion mechanisms. These mechanisms are sensitive to phonological similarity, and this could explain why—one may argue—OM's substitutions occur mainly between phonologically similar letters. Note, however, that phoneme-to-grapheme conversion mechanisms should also support OM's performance in oral spelling, and, therefore, analogous substitutions should occur in the oral and the written spelling tasks. Our data, however, tell another story: substitutions differ, both qualitatively and quantitatively, between these tasks.

In conclusion, the hypothesis that phonological similarity is at the basis of OM's substitution is not supported by the data collected in various tasks (and further evidence will be presented later). Once we have ruled out phonological similarity, we can concentrate on the hypothesis that substitutions involve pairs of physically similar

TABLE 4

Percentage of Letter Confusions Observed While OM Wrote Letters in Print with Uppercase Font (*targets* on the *vertical* axis, *responses* on the *horizontal* axis).

	A	B	C	D	E	F	G	H	I	L	M	N	O	P	Q	R	S	T	U	V	Z
A					0.02								0.01								
B				0.61		0.17				0.07	0.17	0.1		4.52		0.07		0.14			
C							1.28							0.01		0.01	0.07				
D		0.5	0.13				0.05			0.05			0.08	0.37		0.08	0.13	0.08			
E	0.02					0.01	0.01		0.02	0.01											
F		0.11			0.04				0.04					0.37			0.04	2.12		0.07	1.02
G		0.05	3.89	0.21						0.07		0.02			0.28	0.02	0.26				
H							0.13			0.38		0.25							0.01		
I					0.08	0.01				0.03						0.01		0.08			
L							0.01	0.04				0.06		0.03		0.16	0.03	0.04		0.1	0.03
M		0.06								0.02		4.89		0.04		0.02		0.04			
N				0.03			0.01	0.1		0.02	3.1			0.04		0.04	0.01	0.01	0.03		
O	0.01									0.01											
P		0.86	0.02	0.23		0.05				0.02	0.05	0.02				0.09	0.05	0.12			
Q							1.05									0.35					0.35
R		0.06	0.03	0.01		0.02			0.01	0.09	0.01			0.13			0.05			0.03	0.04
S			0.16				0.02									0.01					0.02
T			0.02	0.06	0.01	0.27			0.06	0.17		0.01		0.08		0.04	0.01			0.02	0.03
U					0.03				0.05	0.03											
V		0.04				0.04				0.17											0.13
Z			0.03			0.79	0.13		0.03	0.29						0.06	0.13	0.1		0.03	

Note: Targets on vertical axis; responses on horizontal. The confusion probabilities for the letter pairs *U-V* and *V-U* are not reported—see text for details.

letters. A first objective is to define which physical aspects of letters determine the pattern of substitutions found in our patient. In line with previous research, we examined two possibilities: similarity in terms of letter global shape, and similarity in terms of letter strokes. A series of analyses were carried out to adjudicate between these alternatives.

Letter Substitutions: Letter Shape vs Stroke Similarity

Letter Shape Similarity. To determine whether letter shape similarity affected letter substitutions, Rapp and Caramazza (1997) and Zesiger et al. (1994) examined similarity measures obtained in letter identification tasks. The probability of confusing letters presented visually, and in conditions preventing perfect identification (e.g., because of brief or masked exposure), was taken as an index of letter shape similarity. That is, high confusion ratings were equated to high visual similarity. Confusion ratings were essentially used as predictors of the substitution errors committed by the dysgraphic patient. We adopted an analogous approach to determine the contribution of visual letter similarity on OM's substitutions.

We considered the letter confusion matrices reported in a number of studies (Fisher, Monty, & Glucksberg, 1969; Gilmore, Hersch, Caramazza, & Griffin, 1979; Pew & Gardner, 1965 (data cited in Fisher et al, 1969); Townsend, 1971). We refer to these matrices as visual confusion matrices. The studies differed with respect to the procedure used to boost letter identification errors, which varied from reduced stimulus exposure, to forward or backward masking. The data of *six* visual confusion matrices were entered in regression analyses and served as predictors of OM's letter substitutions.

The visual confusion matrices are valid predictors IF the capital letters used to determine visual similarity, and the capital letters printed by OM have similar shapes. Three studies (Fisher et al., 1969; Gilmore et al., 1979; Pew & Gardner, 1965) included examples of their test items. These items are shown in Fig. 5, along with samples of the corresponding letters printed by OM. As it can be seen by inspecting Fig. 5, OM's letters closely resemble those employed in the studies, a fact that justifies our use of the visual confusion matrices. It should be noted that the visual confusion

FIG. 5. Examples of letters printed by OM, and of the stimuli presented in the letter recognition task by Fisher et al. (1969), Gilmore et al. (1979), and Pew and Gardner (1965). We show only the stimuli reported in all the studies.

matrices were based on the English alphabet, and that this alphabet contains five letters (*J, K, W, X,* and *Y*) that are not part of the Italian alphabet. The cells corresponding to these five letters had then to be excluded, and as a consequence the predictive power of the visual confusion matrices decreased. However, the exclusion of a certain letter is problematic only if the letter was frequently produced as incorrect response. Fortunately, this was not true for the letters that we had to exclude. In fact, within the six visual confusion matrices that we examined, only two times (6%) were the letters *J, K, W, X,* and *Y* among the five letters most frequently encountered as errors; in contrast, eight times (26%) they were among the five letters most rarely produced as errors. In sum, there seem to be no severe consequences from having excluded a few letters.

We ran a distinct regression analysis for each visual confusion matrix. The cells corresponding to the letter *I* have been excluded, because of the variability with which OM printed this letter. The R^2 values obtained in these analyses were never above .05 (see Table 5), which means that the data from visual confusion matrices can account for very little of the distribution of OM's substitutions. We used various confusion matrices, and this makes it very unlikely that our findings reflect idiosyncrasies in the procedures adopted to obtain these matrices.

A direct measure of the similarity existing among OM's letter shapes was obtained by asking 10 college students to rate samples of letters printed by OM for shape similarity. Letters were judged on a 7-point scale, where 1 meant ''very dissimilar'' and 7 meant ''very similar.'' The ratings were used to predict OM's letter substitutions. The obtained R^2 (.06) was fairly low, and was equivalent to the R^2 values found when visual letter confusion matrices were used as predictors. In sum, the results of different types of analyses demonstrate that the contribution of letter shape similarity in OM's substitutions is essentially insignificant. We can thus rule out one account of OM's substitutions—that they reflect letter shape similarity. Does the hypothesis that stroke similarity underlies OM's substitutions fare better? In other words, are confusability measures based on letter stroke similarity valid predictors of OM's substitutions?

Stroke similarity. To address the latter questions, we need (a) to determine the repertoire of strokes used by OM and (b) to acquire a measure of letter similarity based on stroke form. This can be accomplished in a number of procedures, each using a different set of parameters for defining the stroke repertoire. Our goal was to adopt a procedure with a limited number of parameters. Our procedure can be summarized as follows. We first identified the inventory of strokes. We followed the

TABLE 5

R^2 Obtained from Regression Analyses with Visual Confusion Matrices as Predictors

Predictor—Study	R^2
Fisher et al. (1969)—Condition 1[a]	0.02
Fisher et al. (1969)—Condition 2[b]	0.03
Gilmore at al. (1979)	0.04
Pew & Gardner (1965)	0.05
Townsend (1971)—Condition 1[c]	0.05
Townsend (1971)—Condition 2[d]	0.02

[a,b] Letters were shown for 200 and 400 ms in Condition 1 and 2, respectively.

[c,d] Letters were presented with and without mask in Condition 1 and 2, respectively.

operational definition of stroke adopted in previous studies (see e.g., Black et al., 1989; Lambert et al., 1994), according to which a stroke corresponds to a movement segment starting and ending at points where the pen is lifted off the writing surface, or where the pen is stopped momentarily. To determine the number and typology of strokes of each letter, the patient printed a letter repeatedly, while being watched by two observers. There was full agreement between the observers on the strokes composed by OM. Figure 6 provides an illustration of the strokes identified for each letter.

Two dimensions seem crucial for characterizing a stroke: its shape and the direction of the movement needed to form it. The parameters used to classify OM's strokes capture these dimensions, and they relate to the following features: (a) orientation (horizontal, vertical, or oblique); (b) direction (upward vs downward); (c) shape (linear, circular, semicircular, semioval, curvilinear); and (d) starting point. The latter parameter specifies the point at which the stroke starts on a vertical axis: top, middle, and bottom. Figure 6 shows the repertoire of OM's strokes and how they are distributed across uppercase letters. Note that our parameters do not encode important stroke features, such as stroke size, and the order in which a letter's strokes are printed. As a consequence, our procedure does not capture some critical discrepancies among letters. For example, according to our procedure the letters *A* and *V* have an identical stroke—the oblique and downward stroke. From a temporal perspective, however, this stroke is different in the two letters—it is the first stroke in the letter *V* and the second stroke in the letter *A*. The fact that our measure of stroke similarity considers only features relating to stroke shape and direction certainly limits its predictive power.

For each letter pair, we calculated a stroke similarity rating. Each rating was based on two terms. One term was the ratio between the number of strokes shared by the two letters and the number of strokes composing the two letters. For example, the letters *B* and *D* share 2 strokes, and together have 5 strokes; their ratio is then equal to 0.4. The other term was the probability of observing a particular error. This probability is likely to vary as a function of the number of erroneous letters sharing a given

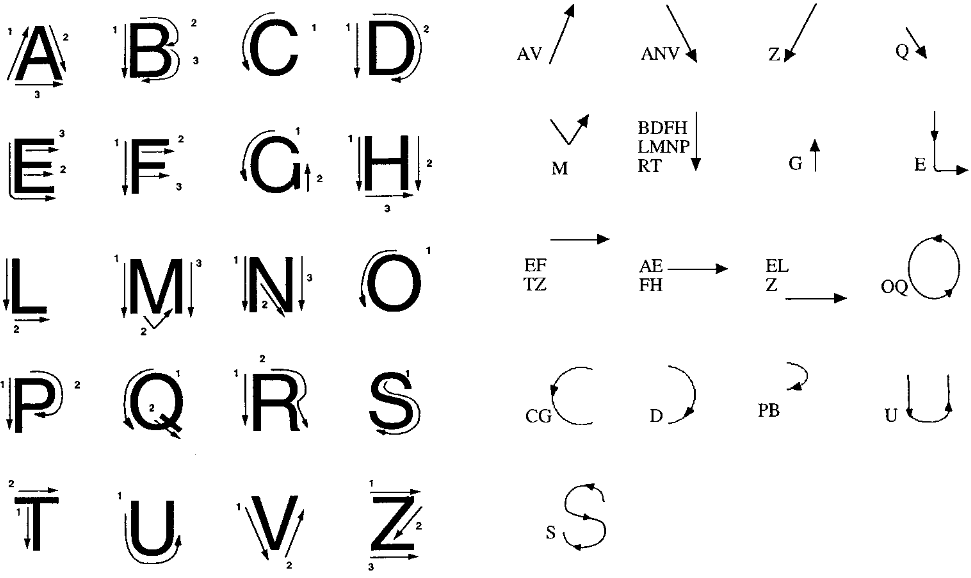

FIG. 6. Left: Strokes composing OM's uppercase letters (the numbers indicate the order with which the strokes were printed: 1 = first, 2 = second, 3 = third). Right: stroke distribution.

stroke. Thus it is equal to 1/2 for two letters, to 1/3 for three letters, and so forth. Stroke similarity ratings were obtained by multiplying the two terms. For example, the stroke similarity rating for the pair *B-D* is given by (2/5) × (1/9; there are 9 letters sharing these strokes), and then it is equal to 0.04.

Stroke similarity ratings were entered in the regression analysis as predictors of OM's substitutions. We obtained an R^2 value of .25. This value is far larger than the one found when data from visual confusion matrices or ratings of letter shape similarity were used as predictors. Multiple regressions provide further evidence that stroke similarity ratings are better predictors. In one type of analysis, stroke similarity ratings and visual confusion matrices were both entered as predictors. We ran a separate analysis for each of the six confusions matrices described above. In a second type of analysis, the predictors were stroke similarity ratings and letter shape similarity ratings. Two results were consistently found in both types of analyses: first, the inclusion of visual confusion matrices did not raise the R^2; second, visual confusion matrices and letter shape similarity ratings never turned out to be significant predictors (ts < 1).

To further prove the role of stroke similarity in OM's substitutions, we carried out a second type of analysis. We contrasted letter pairs with error rates $\geq 0.1\%$ (high-error set; $N = 43$) and letter pairs with error rates ranging between 0.01 and .1% (low-error set; $N = 80$). If number of shared stroke is crucial, we should find greater stroke similarity ratings for pairs in the high-error set. The results are in line with this prediction: stroke similarity ratings were significantly greater in the high-error than in the low-error set ($p < .001$). We thus obtained consistent results with different procedures (planned comparisons and regression analyses), a fact assuring us that our findings do not depend on the use of a particular procedure.

The data of all analyses converge on the conclusion that stroke similarity, rather than letter shape similarity, plays a significant role in determining the incidence and distribution of OM's substitutions. Obviously, stroke similarity ratings are far from perfect predictors. For example, although the letters *O* and *Q* supposedly share a stroke, these letters were never confused. Also, stroke similarity ratings are identical for symmetrical pairs (i.e., pairs composed of the same letters, such as *B-P* and *P-B*). Consequently, we should expect similar error rates for symmetrical pairs—e.g., between *B-P* and *P-B.* However, OM's substitutions show a different pattern; for example, the error rate was 4.52% for $B \rightarrow P$ and 0.86% for $P \rightarrow B$, and it was 1.28% for $C \rightarrow G$ and 3.89% for $G \rightarrow C$ (for both comparisons, McNemar test, $p < .0001$). These inconsistencies suggest that factors other than stroke similarity affect the occurrence of OM's substitutions. What these other factors are is an issue that we will address later. Nevertheless, it is impressive that despite all its limitations, a similarity measure as simple as ours can account for a substantial proportion of OM's substitutions. This certainly plays in favor of the hypothesis that letter strokes are critical in determining the substitutions committed by OM.[5] Additional evidence pointing to the importance of letter strokes was obtained when OM wrote words in cursive.

Cursive Writing

A set of 11,813 words was dictated to OM, and he wrote them in cursive and with lowercase letters. A premise is much needed here: more difficulties were encountered

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[5] As we have seen, OM produced stroke errors consisting in the addition or omission of a stroke. If letter-form representations encode letter strokes, it is not inconceivable that, when these representations are damaged, we may observe stroke errors.

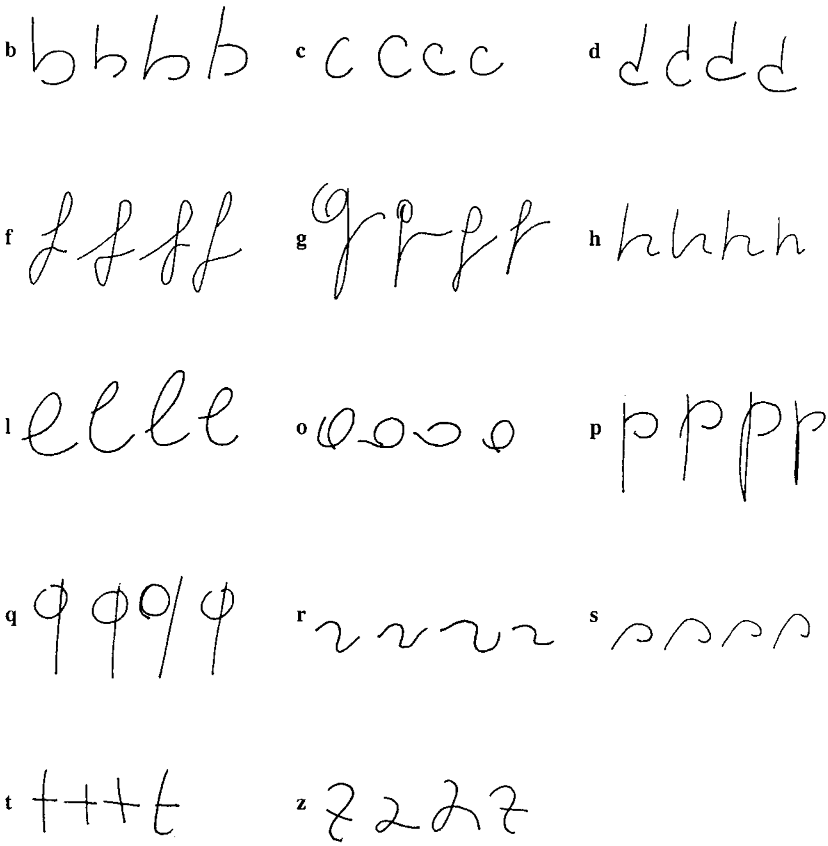

FIG. 7. Examples of the lowercase and cursive letters printed by OM and retained for analyses.

in analyzing cursive than print. OM's cursive was perfectly intelligible, as can be noted in the examples in Fig. 3. However, not all his cursive letters were suited to the purpose of quantitative analysis. This was the case for the letters that were written almost identically—that is, the letters *a* and *e,* and *n, u,* and *v* (to improve clarity, cursive stimuli are presented in lowercase). These letters were excluded from analyses. Moreover, we noticed a considerable variability in letter shapes, in part due to printing the letters jointly—the ''legato'' style of cursive—which allows writers to slightly modify letter composition depending on the context (Wing, 1979). Variability was extreme with the letters *m* and *i,* and they were also removed from analyses. We thus remained with a subset of 14 letters (see examples in Fig. 7). For these letters, the distribution of substitution errors is presented in the confusion matrix of Table 6.[6]

Ideally, one would replicate the analyses of stroke similarity carried out for print. Unfortunately, this is not possible. Because of the variability with which cursive letters were formed, the shape, direction, and orientation of strokes are subjected to

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[6] In cursive, word errors occurred with a probability comparable to the one reported for uppercase print (phonologically plausible errors = 7.2%; stress errors = 0.9%). In cursive, we also observed errors consisting of the deletion of a geminate letter (*gallo* [rooster] → galo) and of the deletion of the *c* in *sc* clusters corresponding to the phoneme /ʃ/ (e.g., *scena* → [scene] sena). All these errors can be explained by a damage to stored orthographic forms. Letter additions, letter deletions, and stroke errors were also observed in cursive. The latter errors, because of the difficulties in scoring cursive, were not analyzed in detail.

TABLE 6
Percentage of Letter Confusions Observed while OM Wrote Letters in Cursive and with Lowercase Font

	a/e	b	c	d	f	g	h	l	o	p	q	r	s	t	z	Total
b				25.24	0.4			0.06		3.83						29.53
c				0.03				0.02		0.02			0.04	0.04		0.15
d	0.04	2.26	0.29		0.04	0.04		0.29		0.08		0.04		0.38		3.46
f								0.66					0.05	0.33	0.1	1.14
g	3.73	0.03		0.83	0.22			0.03	0.15	0.09	0.09	0.03	0.03			5.23
h		0.2			0.2							0.2				0.6
l			0.04		0.02							0.04		0.08		0.18
o																0
p		3.47		0.466	0.11								0.03	0.09		4.166
q						6.89			0.86	0.86						8.61
r			0.01			0.02	0.02	0.06					0.01		0.03	0.15
s			0.05												0.05	0.1
t		0.01	0.01	0.01				0.01		0.01		0.02				0.07
z													0.09	0.04		0.13

Note: Targets on vertical axis; responses on horizontal.

slight changes. In these circumstances, we cannot define the repertoire of strokes that are consistently used for composing the letters, nor can we determine stroke similarity ratings that apply to the whole corpus of letters printed by OM. We had then to choose a different type of analysis, whose objectives were certainly more modest. The analysis hinges on the fact that letters have different strokes across scripts. Thus, letters that have common strokes in one script might not do so when printed in another script. This fact would have implications for OM's substitutions. If stroke similarity varies across scripts, and if stroke similarity affects substitutions, then his substitutions would also be subjected to changes across scripts. This prediction was examined by comparing the substitutions found while OM wrote 11,813 words under dictation in cursive and print (uppercase).

It is particularly informative to consider letter pairs that generated a large number of substitutions. An illustrative example is provided by the letters *F, T,* and *Z.* In print, these letters share multiple strokes, and we expect them to substitute one with the other. Indeed, this occurred quite frequently—we counted 106 errors of this sort. In cursive, the letters *f, t,* and *z* seem not to share any stroke, even when different variants of these letters were taken into account (see Fig. 7). Remarkably, the cursive letters *f, t,* and *z* were exchanged for one another only nine times. Substitution errors involving the letters *C* and *G* have been frequently encountered in print ($C \rightarrow G = 92$; $G \rightarrow C = 106$). The letters *C* and *G* share a stroke in print, but not in cursive. In this latter format, substitutions involving *c* and *g* were totally absent, as expected. It should be noted, however, that in cursive the letter *g* has a stroke in common with the letter *a/e* (remember that in this format the letters *a* and *e* were essentially written identically). The letter *a* was substituted by the letter *a/e* 98 times. However, in print the letter *G* was never substituted by either the letter *A* or the letter *E,* as we expected, given that neither the letter *A* nor the letter *E* shares strokes with the letter *G.*

A few letters seem to share strokes in both print and cursive, and with them we expect to observe substitutions in both scripts. This holds for the letters *B, D,* and *P* and their counterparts *b, d,* and *p.* Substitutions were frequently encountered among these letters, in both print and cursive (170 vs 701; McNemar. $p < .0001$). The higher incidence of substitutions in cursive is probably explained by the fact that OM wrote faster in cursive than in print. At a faster speed, error rate typically increases (Dell, 1986). Incidentally, in cursive we noted instances where the letters *m* was written without a horizontal stroke, resembling the letters *n* or *u.* We also noted cases where the letters *n* and *u* were written with an additional horizontal stoke, appearing like the letter *m*. These errors are expected if stroke similarity affects OM's substitutions.

The consistencies and discrepancies found between cursive and print do not occur randomly; instead they seem to follow a rather predictable pattern reflecting whether letters have common strokes in both scripts. Moreover, substitutions in cursive predominated between letter pairs sharing common strokes. This finding converges nicely with the results obtained in uppercase, and it corroborates the conclusion that number of shared strokes is a key factor in OM's substitutions. There are two additional implications of the data obtained in cursive that are worth stressing. First, the fact that while writing in cursive, OM did not print letters in other formats, along with the fact that his cursive letters were well formed, confirms the conclusion that access to the allographic system is intact. Second, the comparison between print and cursive is relevant for the phonological account, the hypothesis that sound similarity affects OM's substitutions. The finding of marked variations in the error distribution of the two scripts is problematic for the phonological account. In fact, this account would predict analogous error patterns in print and cursive.

Of course, stroke similarity cannot account alone for the pattern of substitutions observed in print and cursive, and other factors must be at play in determining the occurrence of OM's substitutions. OM's large error corpus offers a unique opportunity to examine other possible factors, and we tackle this issue in the next sections. By characterizing the factors underlying OM's errors we can acquire a better picture of the letter-form representations accessed in written spelling.

A Letter Frequency Effect?

Psychologists have accumulated an abundant mass of data showing that the frequency with which a stimulus is encountered or a response is produced is a significant predictor of performance speed and accuracy. In reading, for example, high frequency words are recognized faster than low frequency words (see e.g., Monsell, Doyle, & Haggard, 1989), and an analogous difference is found in picture-naming between pictures with high vs low frequency names (Wingfield, 1968). In the domain of motor performance, we can cite numerous experimental findings indicating that accuracy and speed are highly correlated to increased familiarity with the task (e.g., Van Gallen, 1980). Particularly relevant in the present context are the neuropsychological findings demonstrating that frequency may affect patient performance. In some patients with selective deficits in speaking, reading, or spelling, errors are more numerous for low than high frequency words. Letters also vary for frequency of occurrence in a given language (for English, see e.g., Solso & King, 1976). Does *letter frequency* affect the substitutions involving physically similar letters? The contribution of letter frequency was examined in other patients with apparent letter-form deficit, and the results were mixed: a frequency effect was found in one patient (MP, Black et al., 1989), but not in another two (FT, Del Grosso Destrieri et al., 2000; FB, Lambert et al., 1994). The fact that relatively small error corpora have been used was a limitation of these studies, and OM's large data set may offer a better opportunity to clarify the role of frequency.

Letter frequency was calculated by counting the occurrence of each letter in the word sample written by OM in uppercase font. This sample is sufficiently large (over 18,000 words) to provide a reliable estimate of letter distribution in Italian. Letter substitutions and letter frequency turned out to be significantly and inversely correlated ($r = -.49$, $p < .05$), a finding indicating not only that letter frequency affects letter substitutions, but also that less frequent letters tend to be more vulnerable. A reasonable expectation is that less frequent letters would not be produced as incorrect response—this is a prerogative of very frequent letters. In OM's substitutions, we found evidence conforming to this expectation when we compared symmetrical pairs of uppercase letters, such as *C-G* and *G-C*. Suppose that one letter of the pair is more frequent than the other—in the preceding example, in Italian, the letter *C* is more frequent than the letter *G*. This asymmetry would have implications for the distribution of substitution errors, in that the more frequent letter of the pair should be prevalently produced as incorrect response. That is, the error $G \rightarrow C$ should be encountered more often than the error $C \rightarrow G$. To test this prediction, we analyzed the letter pairs with an error rate $\geq$.1 and their symmetrical pairs (the analysis included 92% of the substitution errors). In this way we considered the errors corresponding to the pairs *C-G* and *G-C*, *B-P* and *P-B*, *L-R* and *R-L*, and so forth. The error rates were then divided into two groups, according to the relative frequency of the substituting letter—higher frequency (e.g., $G \rightarrow C$) and lower frequency (e.g., $C \rightarrow G$). In each group there were 29 observations. Error rate was significantly greater for responses containing more frequent letters (means = .75% vs .30%; $t(29) = 2.86$, $p < .01$), a finding indicating that more frequent letters were preferentially used as response. Altogether the results reveal that letter frequency is one of the factors affecting OM's substitutions, since it determines not only the extent to which a letter is substituted, but also the extent to which a letter substitutes for the target one. We should further note that the letter frequency effect provides the basis for explaining why error rates were different between symmetrical pairs like *C-G* and *G-C*. These intriguing differences could simply reflect frequency discrepancies within letter pairs.

A Consonant–Vowel Distinction?

Within the corpus of OM's substitutions, we observed a striking *dissociation* between consonants and vowels. Substitutions were far more frequent with consonants than vowels (2.09% vs 0.08%). Moreover, almost invariably (96.5%) consonants were substituted by other consonants. These discrepancies are reminiscent of patients with grapheme buffer deficits selectively affecting consonants or vowels, or whose substitutions consistently occurred either between consonants or between vowels (Cubelli, 1991; Caramazza & Miceli, 1990). To account for the selective deficits of these patients, it was proposed that consonants and vowels are distinctly represented, so that, in conditions of brain lesion, they can be independently damaged. And to account for the appearance of consonant–consonant and vowel–vowel substitutions, it was further proposed that letter identity and consonant/vowel status are distinctly represented and could be independently damaged. In this way, if access to letter identity is selectively damaged, the availability of information about the consonant/vowel status restricts the choice of the incorrect response among letters with the same status. One could explain OM's errors along the same lines. Because information about the identity of consonants is selectively damaged, his errors are restricted to consonants. But because information about consonant/vowel status is preserved, only consonant–consonant substitutions would appear. Is this a tenable account? That is, do we need to appeal to hypotheses stating consonant/vowel distinctions to account for OM's pattern of dissociations? We do not think so. Instead, we are inclined to interpret his dissociations as an artifact of letter frequency and stroke similarity.

Earlier, we showed that letter frequency affects OM's substitutions, and we demonstrated that substitutions are less common for frequently produced letters. Vowels are among the most frequent letters, and this can (in part) account for the scarce incidence of substitutions with vowels. Furthermore, we should note that in OM's handwriting, the vowels *E, I,* and *U* are composed of ‘‘unique’’ strokes, not present in other letters (see Fig. 6). And the letters *A* and *O* are formed by strokes not shared by many other letters. We have shown that substitutions predominantly occur between letters with common strokes, and so we should not be surprised that vowels are rarely subjected to substitutions. Furthermore, because of the typology of their strokes, vowels are not expected to frequently substitute for other letters. This could explain why consonants are substituted by consonants rather than by vowels. The data in cursive provide direct support for our hypothesis. The letters *g* and *a/e* share a stroke, and *g* → *a/e* substitutions were noted. The latter finding demonstrates that consonant–vowel substitutions can be found when the letters share a stroke. In conclusion, the consonant/vowel dissociations observed in OM seem to be more a *coincidence*—of letter frequency and of stroke overlap—than the result of representing the consonant/vowel status.

Geminate Letters

Whether a letter is a geminate was one of the factors contributing to OM's errors. Within the corpus of OM's substitutions, we observed 68 errors like ca*nn*oli [cannoli] → CA*MM*OLI, characterized by the exchange of both geminate letters. We refer to errors of this type as *geminate substitutions.* Errors like can*n*a [cane] → CAN*M*A, where only one geminate letter was changed, were observed less frequently than geminate substitutions (68 vs 11; McNemar test, $p < .001$; these errors accounted for 1.7 and 0.3% of the 4017 geminates in the corpus, respectively). It seems, then, that identical substitution errors are likely to be observed with pairs of geminate letters.

How can we characterize geminate substitutions? One possibility is that they arise because the letters are geminate. But these errors can be accounted for without considering geminate letters a special case. For example, errors like ca*nn*oli → CA*MM*OLI can be conceived as the product of two independent substitutions, both accidentally resulting in the identical letter substitution *n* → M. However, OM's data proved this account to be untenable. It predicts that errors identical to those found with geminate letters should *also* be found with nongeminate letters. That is, we should find errors like ca*nt*o → [song] CA*MM*O, where two different letters were substituted for by an identical letter, yielding the exchanges *n* → M and *t* → M. Remarkably, we never noticed an error like ca*nt*o → CA*MM*O in the corpus of 1668 substitutions occurring with nongeminate letters.

Alternatively, one may propose that what matters is if the letter is repeated in the word. Accordingly, the repeated letters *n* in ca*nn*oli and the repeated letters *p* in *p*om*p*elmo [grapefruit] are equivalent. Thus, if a substitution occurs for one repeated letter (e.g., *p*ompelmo → *B*OMPELMO), it is likely that an identical substitution appears with the other repeated letter (e.g., pom*p*elmo → BOM*B*ELMO). Obviously, this account predicts that errors like *p*om*p*elmo → *B*OM*B*ELMO, involving repeated nongeminate letters, are encountered with the same probability of errors like ca*nn*oli → CA*MM*OLI, involving geminate letters. To test this prediction we must only consider the letters that in Italian are geminate (namely all the consonants with the exception of *H* and *Q*). The data proved this prediction to be incorrect: errors like *p*om*p*elmo → *B*OM*B*ELMO were found on 0.13% (11/8,205) of the repeated nongeminate letters, a proportion more than 10 times smaller than the one obtained with geminate letters (1.7%). In short, all the evidence indicates that geminate substitutions arise because letters are *geminate.* We can then conclude that letter gemination is one of the factors affecting OM's substitutions.

The Organization of Letter-Form Representations

By comparing OM's performance in various tasks, it was possible to pinpoint the causes of the letter substitutions copiously produced by our patient in written spelling.

Evidence that substitutions were far more frequent in written than oral spelling restricts the damage to processes specific to written spelling. Furthermore, evidence that letters were perfectly composed and that, in drawing, OM could perform fine movements makes it unlikely that a motor impairment causes his errors in written spelling. Crucially, in both print and cursive, substitutions predominantly involved letter pairs ‘‘looking alike.’’ On the basis of these data, we concluded that substitutions arose because of a deficit at the level of letter-form representations. Once we have established that, OM’s substitutions can be analyzed with the objective of understanding the organization of the letter-form representations accessed in writing.

We demonstrated that stroke similarity is a valid predictor of OM’s substitutions found both in print *and* in cursive. Furthermore, stroke similarity provided the basis for explaining why substitutions varied between print and cursive. On the other hand, measures of similarity based on global letter shape proved to be uncorrelated to OM’s substitutions. Moreover, no evidence was found that substitutions involved phonologically similar letters. These contrasting results invite the conclusions that letter-form representations specify letter strokes, and that letter global shapes and sounds are not, at this level, relevant features. Our results, along with those of a few other patients (Del Grosso Destreri et al., 2000; Lambert et al., 1994; Rapp & Caramazza, 1997; Zesiger et al., 1994), reveal that the letter-form representations accessed in writing encode information about letter strokes.

It was proposed that stroke-based letter representations hold only for uppercase letters (Zesiger, et al., 1994; but see also Teulings, Thomassen, & van Galen, 1986). For more familiar, more rapidly produced fonts (e.g., lowercase cursive), representations of whole letters exist. The findings of OM are not in line with this account. Both in print and in cursive, OM’s substitutions occurred prevalently between letters with common strokes, a finding suggesting that stroke-based letter-form representations support writing in both scripts. If this characterization of letter-form representations is correct, we can further conclude that information about script and font is not relevant at the level of letter-form representations—such information is encoded only within the allographic system (Black et al., 1989; Zesiger et al., 1997).

A relevant issue is to determine the dimensions according to which strokes are specified. In our analyses, we defined strokes in terms of dimensions such as direction, orientation, shape, and starting point, and we obtained letter similarity ratings based on these dimensions. These ratings successfully accounted for OM’s substitutions, a fact inviting the inference that letter-form representations specify the stroke dimensions included in our analyses. We did not consider potentially relevant dimensions such as stroke sequence. Further analyses are needed to determine if and how these dimensions are encoded at the level of letter-form representations. A type of information that is not encoded by letter-form representations is stroke size. Rapp and Caramazza (1997) showed that patients with putative damage to letter-form representations produced similar letter substitutions regardless of letter size. This finding invites the conclusion that letter size is encoded at more peripheral stages (on this point see also Teulings et al., 1986).

Within the general model of spelling presented in Figure 1, the graphemic buffer immediately precedes access to letter-form representations (see Fig. 1). At the level of the graphemic buffer, the letters composing a word are represented as modality independent units—graphemes—accessed to perform various spelling tasks (writing, typing, oral spelling, etc.). The results of detailed neuropsychological investigations characterized the graphemes as complex representations specifying multiple features: letter identity, consonant/vowel status, and letter geminate (Cubelli, 1991; Caramazza & Miceli, 1990; McCloskey et al., 1994; Tainturier & Caramazza, 1996). Consistent with this view, the grapheme ⟨b⟩ in BOOK is encoded as ⟨b⟩ and ⟨consonant⟩, whereas the grapheme ⟨o⟩ is encoded as ⟨o⟩, ⟨vowel⟩, and ⟨geminate⟩. These features are independently represented, so that in conditions of brain damage they can be selectively impaired. This assumption provides the basis for explaining various dissociations observed in acquired dysgraphia, like the one evinced from errors like *b*oo*k* → *P*OO*L* or b*oo*k → B*AA*K. In these errors, the identity of the target letter is lost. However, information about whether the letter is a consonant or a vowel, or whether it is geminate, is preserved. The sparing of this information would lead to exchanges between either consonants or vowels, and between geminate letters (as in b*oo*k → B*AA*K). Analogous stark dissociations arose in OM: his substitutions almost exclusively affected consonants, and a consonant was almost infallibly substituted by another consonant. If we are correct in attributing OM's substitutions to a damage at the level of word form representations, then one question imposes itself: do OM's dissociations arise because letter-form representations specify the vowel/consonant status of letters? We argue that this hypothesis seems implausible on the grounds that OM's consonant/vowel dissociation might very well be a confound of other features systematically varying between consonants and vowels, including frequency and degree of stroke similarity. Consistent with this interpretation, we can then conclude that letter-form representations specify letter identity, *not* whether the letter is a consonant or a vowel. The latter feature is encoded at the preceding level of processing, the graphemic buffer.

With geminate letters, we have noticed a conspicuous number of geminate substitutions, errors characterized by the exchange of both geminate letters as in ca*nn*oli [cannoli] → CA*MM*OLI. In these errors we have a dissociation between (spared) information about letter duplication and (impaired) information about letter identity. There are two general accounts of this dissociation (McCloskey et al., 1994; Taiturier & Caramazza, 1996). On one view, letter identity and gemination are pieces of information distinctly specified within the graphemic buffer. For geminate letters there is a geminate feature, a sort of ''duplicate command,'' whose activation determines the repetition of the motor pattern corresponding to a selected letter. The correct spelling of the word *cannoli* implies the availability of the grapheme ⟨n⟩ and of a geminate feature linked to the grapheme ⟨n⟩. The form representation corresponding to the letter *n* is selected once, and the activation of the geminate feature ensures the letter duplication. Errors like ca*nn*oli → CA*MM*OLI are explained by assuming a problem in selecting the correct letter form representation, but a sparing of the geminate feature. In this way, even if the incorrect letter was selected, the availability of information about letter duplication yields the appearance of geminate substitutions like ca*nn*oli → CA*MM*OLI. The alternative view assumes no special encoding for letter geminates, and their selection is in all respects identical to the one of nongeminate letters: there is a distinct selection process for each letter of the words, either geminate or not. OM's data proved the latter hypothesis to be implausible. Because no distinction is made between geminate and nongeminate letters, we expect to find errors like ca*nt*o → CA*MM*O. Remarkably, however, in a corpus of 1668 errors, we did not observe even one error of this sort. Moreover, if geminate letters are independently selected, one would argue that errors like can*n*a [cane] → CAN*M*A, characterized by the substitution of only one geminate letter, should be encountered more frequently than geminate substitutions. But we observed the exact opposite finding: geminate substitutions were far more numerous. In short, of the two alternative hypotheses, only the one assuming the explicit representation of geminate feature found support in OM's data.

Our interpretation of OM's geminate substitutions assumes that letter-form representations do not specify letter gemination—this feature is made explicit at the grapheme buffer level. From a logical point of view, OM's data would also be compatible with the hypothesis that letter-form representations specify whether letters are geminate. However, the latter solution is far less economical. We must assume that geminates are encoded not only within letter-form representations but also within the letter representations involved in typing and oral spelling. Parsimony, if anything, would lead us to prefer the account that geminate features are encoded at the buffer level. In our view, then, letter-form representations (and perhaps also other letter representations accessed in typing and oral spelling) only store letter-specific information (e.g., their strokes or their sound).

A final point concerns letter frequency. We showed that letter frequency affected OM's substitutions (for similar findings see also Black et al., 1989). Our data are consistent with reaction time data showing that neurologically intact subjects are faster at starting to print high than low frequency letters (Meulenbroek & Van Gallen, 1990; Van Galen, 1980). OM's data lead us to conclude that access to letter-form representation is modulated by frequency. Frequency effects have been demonstrated in various tasks with words—from naming to reading to writing. Although we are far from having a comprehensive account of frequency effects, evidence that frequency plays a role at the levels of letter-form representations is an important result in that it indicates that analogous principles underlie representations devoted to different stimuli (words vs letters), and used in different modalities (spoken vs written).

Neuroanatomical Considerations

Because of their massive brain lesions, neuropsychological patients cannot inform us on where exactly letter-form representations are processed in the brain. Nevertheless, their lesions, although widespread, may help us to disclose some general principles of brain functional organization. Two facts are particularly relevant in this context. First, in all the patients documented to date, substitutions involving physically similar letters were consistently associated to bilateral or left-hemisphere lesions—a selective right-hemisphere lesion was never reported. Second, patients' deficit was invariably restricted to written spelling, their ability to drawing being preserved (for this dissociation in other forms of dysgraphias see, e.g., Kapur & Lawton, 1983; Roeltgen & Heilman, 1983). Together, these two facts indicate that there are mechanisms specifically devoted to the motor production of linguistic forms (letters), and that these mechanisms reside in the left hemisphere. Neuropsychological evidence suggesting that the left hemisphere holds the letter representations accessed in reading has recently been obtained (Chanoine et al., 1998; Miozzo & Caramazza, 1998). The latter results converge with the ones obtained in written spelling and invite the conclusion that any level of language processing—from the fundamental units (phonemes and letters) up to sentences—are stored within the left hemisphere. The neuropsychological results confirm the classical view of the left brain as the repository of language, although they are inconsistent with views assigning some language functions (e.g., in reading; Coltheart, 1980; Coslett & Saffran, 1994; Zaidel & Schweiger, 1984) to the right brain. Our conclusion is also in contrast with the recent proposal that the left brain is specialized for the perception and production of rapidly changing information (Tallal, Merzenich, Miller, & Jenkins, 1998).

CONCLUSIONS

The detailed investigation of OM's letter substitutions provides strong support for the hypothesis that in written spelling, a separate level of processing is devoted to the encoding of letter forms, and that strokes constitute the building elements of the letter-form representations accessed in different scripts (print vs cursive). As in other types of representations, access to letter forms is sensitive to frequency of use. Whether a letter is a consonant or a vowel, or geminate, does not appear to be features specified at the level of letter-form representation—these features are encoded only at preceding levels of processing.

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