From Graphemes to Abstract Letter Shapes: Levels of Representation in Written Spelling

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The letter substitution errors of 2 dysgraphic subjects who, despite relatively intact oral spelling, made well-formed letter substitution errors in written spelling, were studied. Many of these errors bear a general physical similarity to the intended target. Analyses revealed that this similarity apparently was based on the features of the component strokes of letters rather than on visuospatial characteristics. A comparison of these subjects’ letter substitution errors with those of 2 other individuals with brain damage, whose damage was at a different level of processing, revealed that the latter subjects’ errors are not explicable in terms of stroke-feature similarity. Strong support was found for the computation of multiple representational types in the course of written spelling. This system includes a relatively abstract, effector-independent representational level that specifies the features of the component strokes of letters.

Any theory of written spelling must address the following question: How does one go from the knowledge that the name of the country whose capital is London consists of the grapheme set E-N-G-L-A-N-D to the actual writing of the specific forms england (or England or england) with the right hand, left hand, on paper, on the blackboard, with a pencil tied to a foot, or even in icing on a cake or by arranging pebbles? That is, how does one account both for a person’s ability to express orthographic knowledge in a relatively similar manner across modes of execution while also allowing for the clearly different requirements of each execution mode? Current theories of written spelling generally agree that, to explain a person’s ability to generate similar shapes with different limbs or execution modes, it is necessary to posit relatively abstract, effector-independent representations that specify the forms of letters. Thus, the question is not so much whether abstract representations of letter form actually play a role in the writing process but what type of information is represented at this abstract level of letter-form representation: Is it motoric? Visuospatial? Temporal?

In this article we present an analysis of the impaired writing performance of 2 dysgraphic subjects who made well-formed letter substitution errors in written spelling (e.g., writing F-A-P-L-E for TABLE while correctly saying [ti, ei, bi, el, i]). The fact that oral spelling performance is relatively intact testifies to the integrity of the amodal central levels of representation and processing that presumably underlie both written and oral spelling. Furthermore, the well-formedness of the written errors indicates that the affected processes are more central than those involved in peripheral aspects of motor control. Thus, the letter substitution errors produced by these subjects should provide information about the abstract representations of letter form that are used in written spelling.

We address two sets of issues. The first concerns the nature of the letter-form representations implicated in the errors of these subjects. We consider whether these representations are primarily visuospatial in nature (i.e., specifying the spatial configuration of letter shapes in terms of features like those used in visual processing) or whether they represent information about the characteristics of the strokes required to produce letters. We also examine whether these affected letter-form representations are effector independent and, in the Discussion section, consider whether the representations that are used in writing also are used for visual letter recognition.

The second set of questions concerns an evaluation of the basic assumption that spelling involves the computation of several distinct representational types. Specifically, we consider the distinction between amodal graphemic representations (which presumably underlie both written and oral spelling) and abstract letter-form representations (which presumably are used only in written spelling). We examine
this representational distinction by contrasting detailed aspects of the error patterns of two sets of individuals, each with hypothesized damage to one of these representational types and not the other.

From our evaluation of these two sets of questions, we draw two conclusions: First, there is strong support for the view that the spelling process involves computing multiple representational types. Second, within such a system there is an effector-independent representational level\(^1\) that specifies features of the strokes required to produce letter forms.

Use of Subjects With Brain Damage

The procedure that we follow involves first localizing the deficits of the subjects to one or more components within a functional architecture of the spelling process. The characteristics of their errors are then used to provide information about the affected representational level. Although it is beyond the scope of this article to present arguments about the logic and assumptions involved in using impaired performance to investigate normal processing (see Caramazza, 1986, 1992; Shallice, 1988), we briefly discuss certain benefits of using data from impaired performance.

Our arguments are based on analyses of the relationship between target letters and error responses. One advantage of using impaired subjects is that they typically make more errors than unimpaired subjects. Whereas normal errors may arise from the occasional malfunctioning of a cognitive component, brain damage may greatly increase the error rates. For example, in the case at hand, normal elderly control subjects exhibited a 0–0.2% rate of letter substitution errors in writing to dictation, and our control subjects with brain damage produced letter substitution errors at rates of 3.5% and 3.2%.

More important, however, is the fact that with subjects with brain damage, we may be able to firmly establish that the errors originate from a particular locus within the cognitive system. When working with unimpaired subjects in a situation in which errors can originate from multiple cognitive mechanisms (as is the case with letter substitutions), it is often extremely difficult to establish the locus of specific errors. This, in turn, may make it difficult to draw inferences about the functioning of a particular cognitive mechanism from the characteristics of a set of errors.

In short, a large database of errors and confidence about their origin constitute especially salient benefits of working with data from impaired performance (for the analyses we present here). Note, however, that we do not use data from individuals with brain damage specifically to draw conclusions about the characteristics of normal writing errors; rather, we use the data to draw conclusions about the nature of normal letter-form representations. It could turn out that unimpaired subjects make similar kinds of errors, albeit with much less frequency, than impaired subjects, or, alternatively, that the errors of those with brain damage arise from damage to a different mechanism than the one that only infrequently malfunctions in unimpaired individuals. Although it would be interesting to sort this out, one must remember that the conclusions we reach here specifically concern the content of normal letter-form representations. These claims may, in turn, generate testable predictions about specific patterns of normal writing times, priming effects, error numbers, or error types.

A Model of the Spelling Process

We begin by reviewing the model of the spelling process that informs the work presented here. A schematic representation of this model is depicted in Figure 1. This model distinguishes between the representations and processes that may be used for spelling familiar words and those that can generate plausible spellings for unfamiliar items. For familiar words it is possible to go from a lexical semantic representation to its corresponding lexical orthographic form stored in the orthographic output lexicon. Given that there are no stored representations of the spellings of unfamiliar words, these stimuli are assigned a plausible graphemic representation through the application of sublexical phonology-to-orthography conversion (POC) procedures. For example, the output of the POC procedures for the stimulus [grat] would include spellings such as G-R-O-T or G-R-A-U-G-H-T. The involvement of different mechanisms in the processing of familiar versus unfamiliar material has received empirical support from impairments that purportedly selectively affect one set of mechanisms and not the other (Baxter & Warrington, 1985, 1987; Beauvois & Dérouesné, 1981; Bub & Kertesz, 1982; Goodman & Caramazza, 1986; Hatfield & Patterson, 1982; Roeltgen, Sevush, & Heilman, 1983; Shallice, 1981). Thus, for example, several cases of individuals with brain damage (including one of the individuals in this research) can be understood by hypothesizing that damage affecting the availability of information in orthographic lexical store prevents a semantic representation from making contact with its corresponding orthographic form. As a consequence, there are words whose meanings are familiar but that are treated as unfamiliar items with respect to their form. These are subjected to POC procedures that assign plausible, but often incorrect, spellings (e.g., [yat] → YOT). We refer to such responses as phonologically plausible errors (PPEs).

In the reading (and, to a lesser extent, the writing) literature, there is considerable controversy about the exact formulation of the characteristics and capacities of the procedures for translating print to sound (see parallel distributed processing accounts by Seidenberg & McClelland, 1989; Plaut, McClelland, Seidenberg & Patterson, 1996; but also Coltheart, Curtis, Atkins, & Haller, 1993; Besner, Twilley, McCann, & Seergobin, 1990; for sound to print, see Brown & Loosemore, 1994; Olson & Caramazza, 1994). We do not see, however, that the resolution of this particular controversy should have any consequences for the conclusions we reach here about the content of letter-form representations.

\(^1\) We use the term levels of representation to refer to the different representational types that may be used by different cognitive mechanisms in the course of processing.
We assume that the representations that result from lexical or sublexical POC processing consist of amodal, spatially arrayed graphemes that are held in a temporary memory store—the graphemic buffer—while being assigned a shape or name by subsequent processes dedicated specifically to written or oral spelling (Caramazza, Miceli, Villa, & Romani, 1987; Ellis, 1988; Houghton, Glasspool, & Shallice, 1994; Margolin, 1984; Wing & Baddeley, 1980). We refer to them as amodal to indicate that graphemic representations do not consist of letter names or letter shapes but instead that they are symbolic representations of letter identities. Among the evidence supporting the amodal nature of graphemic representations are the reports of individuals with brain damage who individually exhibit striking similarities in error rates and in error type distributions for both words and nonwords across both spoken and written output modalities (Caramazza & Miceli, 1990; Caramazza et al., 1987; Hillis & Caramazza, 1989; Jonsdottir, Shallice, & Wise, 1996; Katz, 1991; McCloskey, Badecker, Goodmann-Schulman, & Alimonsa, 1994; Piccirilli, Petrillo, & Poli, 1992; Posteraro, Zinelli, & Mazzucchi, 1988).

Beyond the level of the central graphemic buffer, we draw a distinction between the modality-specific mechanisms dedicated to oral spelling and those that are specific to written spelling. This distinction is motivated not only by computational considerations but also by the observation of selective deficits to either modality of spelling output. Thus, individuals have been described with selective difficulties in oral spelling in which, although the specification of amodal graphemes is intact (as evidenced by correct written spelling), the mechanisms responsible for retrieving the names corresponding to these graphemes fail (Bub & Kertesz, 1982; Kinsbourne & Warrington, 1965). By contrast, individuals also have been identified whose oral spelling was relatively intact but who, although they exhibited no generalized motor deficits, had difficulty producing the written forms of words (Anderson, Damasio, & Damasio, 1990; Baxter & Warrington, 1986; De Bastiani & Barry, 1989; Black, Behrmann, Bass, & Hacker, 1989; Friedman & Alexander, 1989; Goodman & Caramazza, 1986; Kinsbourne & Rosenfield, 1974; Patterson & Wing, 1989; Rapp & Caramazza, 1989; Rothi & Heilman, 1981; Zangwill, 1954). These latter cases may be loosely considered to involve deficits affecting processes dedicated to assigning case, font, and shape to the amodal graphemic material held in the graphemic buffer. It is this part of the spelling system that we are concerned with here and that we now consider in more detail.

Processes Subserving Written Spelling Specifically

Theories of written spelling typically posit a number of representational and processing stages beyond the central processes described earlier. These begin with processes responsible for assigning form (case, font, and shape) to the amodal graphemes held in the buffer and end with the execution of neuromuscular commands. A discussion of the execution and control of neuromuscular commands (and deficits affecting these processes) is beyond the scope of

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2 It is noteworthy, however, that the writing performance of individuals with deficits attributable to these relatively peripheral mechanisms has much different characteristics than the writing of the individuals we report on here: individuals with more peripheral deficits produced distorted, often unrecognizable, letters involving misplacement or repetition of strokes, incorrect strokes, and so on.
this article. Instead, we focus on the stages involved in giving form to amodal graphemic material.

As indicated earlier, most researchers agree that, to account for a person's ability to generate similar shapes with different limbs or execution modes, it is necessary to posit a relatively abstract—effector-independent—level of representation that specifies the forms of letters (Lashley, 1951; see Keele, 1981, for a review). For example, a relatively abstract level of "motoric" representation has been invoked to account for striking similarities in the forms of letters produced by individuals when they are using different effectors such as right or left hand or arm (Bernstein, 1967; Merton, 1972; Raibert, 1977; but see Wright, 1990). This level of representation is sometimes referred to as an abstract motor plan. However, although there is general agreement on the need to posit relatively abstract levels of letterform representation, there is little agreement on the number or content of such representations.

In the literature on unimpaired individuals, these issues have been addressed in many ways. For example, some have contrasted the extent to which various characteristics of handwriting performance—spatial, temporal, and force—are reliably invariant across changes in handwriting size, slant, effector, and so on. The reasoning has been that invariances may reveal the content of underlying abstract representations (Denier van der Gon & Thuring, 1965; Keele & Summers, 1976; Lyons, 1964; Merton, 1972; Smyth & Wing, 1984; Stockholm, 1979; Teulings, Thomas- sen, & van Galen, 1986; Viviani & Terzuolo, 1980; Wing, 1978). For example, Hollerbach (1981) found that there was no difference in the time taken by subjects to write letter patterns of two different sizes. Thus, the increase in trajectory length for the larger letters was compensated for by an increase in writing speed, with the result that the overall duration remained constant. Along the same line, Viviani and Terzuolo (1980) found that velocity profiles remained constant across changes in writing speed. This type of evidence has been used to argue for the inclusion of timing information at the level of abstract motor plans. However, a fundamental interpretative problem is that it is difficult to discriminate between the invariances that result from characteristics of the underlying abstract letter-form representations and motor plans and those that reflect characteristics of more peripheral aspects of the motor execution systems. Thus, Teulings et al. (1986) and Wright (1993) argued that temporal constancies might result from the properties of an execution system whose goal is to achieve relatively invariant spatial characteristics across writing speeds, size, and effectors.

Another technique involves the analysis of the costs and savings incurred in transferring a known motor pattern to another mode of execution. Here the reasoning has been that the aspects of production that do not result in transfer costs are represented in an effector-independent manner, whereas transfer costs reflect effector-specific aspects of learning. Using this technique, Wright and Lindemann (1993) concluded that whereas letters and words involve effector-independent representations, strokes are represented at an effector-specific level.

Research efforts in the literature on unimpaired individuals have been directed primarily at understanding the content of motor plans, with less attention paid to separating the stages of planning (but see Wright & Lindemann, 1993). By contrast, patterns of impaired performance have been used to argue that there are at least two relatively abstract, effector-independent representational levels (Ellis, 1979, 1982, 1988; Margolin, 1984): one at which specific letter shapes are generated and another involving the retrieval of the characteristics of the strokes required to create the letter shapes. According to these authors, the first stage in providing form to amodal graphemes is the retrieval of allographic forms from a long-term allographic store of letter shapes. Allographs are the physical variants corresponding to the same abstract grapheme; for example, lower- and uppercase E/e are allographs of the same grapheme, as are the corresponding cursive forms. Importantly, according to these authors, the allographic specification of letter shapes is made in terms of visuospatial features. The allographic level is followed by the level of the graphic motor pattern where, according to Ellis (1988), one derives "the sequence of strokes necessary to create the allograph. . . . It specifies the direction, relative size, position and order of strokes required to form an allograph" (p. 103). The relationship between the graphic motor plan referred to by Ellis and Margolin and the notion of abstract motor plan is not entirely obvious. Although it is possible that they are equivalent, the notion of abstract motor plan is undefined and may in fact be compatible with both the stages of allographic and graphic motor planning that have been proposed by Ellis and Margolin.

Ellis (1982, 1988) and Margolin (1984) based their proposed distinction between stages dedicated to letter-shape assignment versus stroke specification on cases in which brain damage has purportedly affected one stage but not the other. Thus, on one hand, there are deficits in which case, font, or both are relevant, such as those that involve difficulties in producing letters in the intended case (e.g., forza → F-o-r-Z-A; De Bastiani & Barry, 1989) or specific difficulties in writing in lower- versus uppercases (Patterson & Wing, 1989). By contrast, there are individuals who have no difficulties involving case or font, yet they make numerous well-formed letter substitution errors only in written spelling. Although the former cases have been interpreted as resulting from an impairment in the selection or activation of specific allographic letter shapes, the latter, Ellis (1988) argued, "indicate problems in activating appropriate graphic motor patterns in response to input from the allograph level" (p. 111).

We should point out, however, that although there are good reasons to assume that subsequent to the amodal graphemic level (and before the selection of graphic motor patterns) there must be a mechanism for assigning case and font to graphemes, it does not follow that the actual forms of allographs must be specified at such a level (see also Shallice, 1988). For example, if the concept "capital of England" forms the basis for the retrieval of the amodal graphemic representation L-O-N-D-O-N (in certain orthographic contexts), some mechanism must specify that the
first grapheme should be expressed in uppercase and the subsequent ones in lowercase. Nonetheless, there would seem to be no apparent motivation for positing that the specification of case must involve the assignment of shape. Thus, one could imagine the following sequence of events: semantic representation \(\rightarrow\) amodal graphemic representation \(\rightarrow\) case specification for each grapheme position \(\rightarrow\) selection of case-specific graphic–motor plans, and so on. This sequence of events would not require the independent representation of visuospatially based allographic shapes. According to this alternative, the deficits that have been observed involving difficulties in controlling case might be attributed to the mechanism responsible for case specification (however, see Weekes, 1994, for a different suggestion), whereas deficits that selectively affect the availability of one case may arise from the stage of graphic–motor planning in which programs may in fact be organized or indexed by case. Thus, these patterns of impaired performance do not require that we posit a level of representation at which visuospatial letter-shape information is specified.

In summary, there are various proposals about the content of the representations involved in letter-form assignment. These include but are not limited to visuospatial features, information about the sequence, timing and force of strokes, and so on. In this article we attempt to distinguish between two hypotheses regarding the possible spatial nature of the abstract motoric information.

**Issues To Be Addressed**

**Representation of Letter Form**

The 2 individuals whose performance we describe in this article made letter substitution errors primarily in written spelling. Thus, within the framework we have described, these deficits would be generally localized to the cognitive components involved in assigning letter forms. As has been the case for other individuals with apparently similar deficits (Black et al., 1989; De Bastiani & Barry, 1989; Hatfield & Patterson, 1983; Lambert, Viader, Eustache, & Morin, 1994; Weekes, 1994; Zangwill, 1954), a cursory examination of the errors reveals that target–response pairs share what could loosely be described as a “physical” resemblance: \(n \rightarrow h, p \rightarrow d\). There is, however, a fundamental ambiguity concerning the notion of physical similarity. One might mean visual similarity of the type that forms the basis of the confusions of unimpaired individuals who are presented with briefly displayed letters for identification (e.g., confusions between \(A\) and \(R\) and \(F\) and \(P\)). Alternatively, one might mean similarity in terms of the characteristics of the strokes—number, orientation, and direction—required to produce the forms (confusions between \(R\) and \(D\) and \(U\) and \(C\)). An added complication is that many letter pairs that are visuospatially similar (such as \(B\) and \(R\) and \(G\) and \(C\)) also are produced with similar stroke sequences. The classification of such pairs would be ambiguous.

The possibility that written substitution errors might be visually or motorically similar to target letters has been examined in three relatively recent articles. Lambert et al. (1994) examined the extent to which the targets and errors of the individual they studied shared strokes. They determined that 64% of the substitutions involved letters sharing two or more strokes with the target letter. Zesiger, Pegna, and Rilliet (1994) considered the relationship between targets and errors in an individual who exhibited an unusual writing impairment affecting only his left (dominant) hand, leaving right (nondominant)-handed writing intact. These authors examined the extent to which written target–error pairs were similar to the visual confusions reported for normal individuals required to identify briefly exposed letters. Zesiger et al. found that the written lowercase letter confusions involved a substantial degree of visuospatial similarity, whereas the uppercase confusions did not. More recently, Weekes (1994) reported that 70% of the lowercase letter confusions of a dysgraphic individual could be classified as visuospatially similar.

None of these researchers, however, dealt with the ambiguity issue: that some proportion of apparently similar letter pairs probably can be categorized as either visuospatially or motorically similar. Because the researchers did not attempt to distinguish the two representational types, one cannot know which representational type is relevant. Here we present analyses that will address this problem. These analyses should allow us to consider specifically if the letter-form representations implicated in the errors are visuospatial or motoric in nature. The finding of visuospatially based representations would provide strong support for a level of representation at which the forms of letters are represented in a visuospatial manner as suggested by Ellis (1982, 1988) and Margolin (1984). Although the finding of motorically based representations of letter form would not, of course, rule out the possibility of an additional visuospatially based representation, it would constitute clear evidence of the abstract, effector-independent representation of motoric information.

**Stages of Written Spelling**

In the literature involving unimpaired subjects, there have been a few attempts to test multistage models of the presumably hierarchically structured writing system (e.g., Portier, van Galen, & Thomassen, 1983; van Galen, 1980; van Galen & Teulings, 1983). We, too, are concerned with this general issue and specifically test the adequacy of the distinction that has been drawn between amodal graphemic representations that subserve both written and oral spelling and abstract letter-form representations involved only in written spelling. Given the central place that this representational distinction plays within the framework we have adopted, it is crucial to examine its legitimacy. It is important to test basic assumptions such as these even though there currently may not be any well-articulated alternative theories of written spelling that do not include distinctions of this general sort. Furthermore, although there may be no specific alternatives that do without the graphemic/letter-form distinction, in a climate in which
massively distributed schemes for the representation of cognitive skills are being explored, it is critical to establish which basic representational distinctions must be respected.

To examine this question, we take the results of the first set of analyses on the visuospatial versus motoric content of letter-form representations and use them as a further test of the graphemic/letter-form distinction. That is, the graphemic/letter-form distinction has previously been based on a number of computational and empirical considerations that we outlined earlier. Here we subject this distinction to more stringent tests based primarily on what we learn about the content of letter-form representations. We do this by comparing the performance of H.L. and J.G.E. (the participants in our research) with that of L.B. (Caramazza & Miceli, 1990; Caramazza et al., 1987) and H.E. (McCloskey et al., 1994). All 4 of these individuals made well-formed substitution errors in written spelling. However, on the basis of the dissociation between written and oral spelling, we hypothesized that the errors produced by J.G.E. and H.L. arise beyond the graphemic buffer. By contrast, and on the basis of the striking similarity in performance across written and oral spelling of words and nonwords, L.B.'s and H.E.'s deficits were ascribed to the graphemic buffer. According to the model of writing that we have reviewed, representations at these two levels have different characteristics. Information in the graphemic buffer consists of amodal grapheme identities and their positions, representations that are independent of form. By contrast, representations subsequent to the graphemic buffer are hypothesized to include only the abstract, effector-independent information required to provide physical form to the amodal graphemes. We attempted to evaluate whether the letter substitution errors of the two sets of individuals differ in terms of just those features that should be characteristic of the two representational types.

We cannot use the same performance features to test for these critical representational differences as were used to localize the functional deficits to begin with. This is a significant methodological point given that if pattern X (association of written and oral spelling performance) is used to localize a deficit to component A and pattern Y (dissociation between written and oral spelling performance) to component B, then one certainly cannot use X and Y to also argue that the representations at these levels are different. Instead, the evidence used for localization must be independent from the evidence used to examine representational similarities and differences. It is for this reason that we first undertake the analyses of the written letter substitution errors. These analyses will provide detailed information about the content of letter-form representations (visuospatially vs. motorically based). This then can be used as an independent test of the posited distinction between amodal graphemic representation and abstract letter-form representations. If the distinction is meaningful, we expect that the letter substitutions arising from damage to the graphemic buffer should contrast with substitutions arising from letter-form level in that amodal graphemic representations should not be visuospatially or motorically based.

In summary, on the basis of the analyses presented here, we conclude the following: (a) For the individuals we report on, the physical similarity between targets and errors is better described in terms of stroke characteristics than in terms of visuospatial characteristics. (b) This representational level is size and effector independent, subserving (at least) letter-form production with the right and left hands and the right foot. (c) There is strong support for the distinction between the amodal representation of graphemic identity and the abstract representation of letter form.

Case Studies: J.G.E. and H.L.

For each individual we first present a brief case history and then report evidence that their letter substitution errors arise primarily from damage to the written spelling system. Finally, we describe the analysis we used to determine whether the relationship between target-response pairs can be described as visuospatial, stroke based, or neither.

Case 1

J.G.E. was a right-handed man with a master's degree who worked as a high school business teacher until his retirement. At age 73, 18 months before the onset of this investigation, J.G.E. suffered a large left occipital infarct. Magnetic resonance images revealed damage within the left occipital lobe and the posterior temporal lobe. There also was evidence of prior infarcts that affected the right occipital lobe extending to the calcareous fissure, as well as multiple foci of white matter demyelination within the supratemporal white matter and left thalamus (see Figure 2). Whereas the earlier infarcts went undetected by J.G.E., the more recent one resulted in a number of evident
symptoms, including a right visual field cut and right hemiparesis.

At the time of testing, J.G.E.'s auditory comprehension and spoken production were excellent. He showed no signs of visual neglect but exhibited significant problems in letter and object recognition and reading that are the subject of other investigations (Leek, Rapp, & Caramazza, 1994; Rapp, Link, & Caramazza, 1993). J.G.E.'s oral spelling abilities were largely spared, although he exhibited significant difficulties in written spelling. In fact, we noted that J.G.E. often would spontaneously spell a word correctly orally as he was writing it incorrectly. This also occurred when he was asked to write with his eyes closed. Because of right hemiparesis J.G.E. used his left hand in writing; nonetheless, his writing was typically easily legible and his ability to copy figures with his left hand appeared to be intact (see Figure 3). His drawings of objects from memory were only adequate, exhibiting little detail. We do not know whether this was because he found drawing with his left hand difficult or whether it was related to the object recognition difficulties mentioned earlier.

The first stage of testing involved ascertaining whether J.G.E.'s spelling difficulties were confined to the written spelling system. To examine this question, we dictated the same set of 356 words for written and oral spelling. J.G.E. was asked to repeat each word before spelling it and was instructed to write all words in uppercase letters. The list was divided into sublists, each of which was administered on different sessions for oral and written spelling. To avoid confusions that may arise when scoring written responses at a later date, the tester closely observed the stroke patterns of each letter at the time of testing and recorded the identity of
the letters or the sequence of strokes that were produced. This resulted in few ambiguities, all of which were excluded from the error corpus.

We examined the error corpus first for what we refer to as word-level errors and then for letter-level errors. Word-level errors are those that indicate deficits affecting central mechanisms. This category includes errors such as semantic errors (e.g., CHAIR for TABLE) or PPEs (e.g., FLOOT for FLUTE). PPEs, as discussed in the introduction, may indicate a deficit affecting stored orthographic forms that, when unavailable, result in the application of POC procedures to the input stimulus. Semantic errors may indicate either a deficit affecting the lexical semantic representations themselves or a deficit in the retrieval of orthographic lexical forms. J.G.E., however, produced only three PPEs in written spelling and four in oral spelling (e.g., CHAIR —> FLOOT, SURPRISE —> S-U-R-P-I-Z-E) and produced no other word errors in either task. This rate of PPEs was within the range of our normal older controls and allowed us to rule out any significant deficit affecting central lexical processing.

By contrast (see Table 1), J.G.E. produced numerous letter-level errors that involved letter substitutions (ODOR —> CDOR),

\[ \chi^2(5, N = 3,798) = 44.75, p < .0001. \]

For the substitution errors specifically (the error type whose origin we were most concerned with), J.G.E. made 66 errors in written spelling and only 3 in oral spelling. Four older control subjects (aged 71–81 years) who were administered a list of 70 words ranging in length from four to eight letters for written and oral spelling exhibited letter-level error rates in written spelling of 0–1.2%, with letter-level error rates in oral spelling ranging from 0% to 0.5%. Importantly, these normal controls produced no letter substitution errors in written spelling. The contrast between J.G.E. and the older controls demonstrated that J.G.E.'s rate of substitution errors in written spelling was clearly abnormal.

In summary, the absence of significant word-level errors allowed us to rule out a central lexical locus of impairment. Furthermore, given that an impairment at the level of the graphemic buffer should manifest itself comparably in both written and oral spelling, the results presented in Table 1 allowed us to rule out any significant impairment to the graphemic buffer. For these reasons, we are confident that the substitution errors that J.G.E. produced in written spelling arose primarily (or entirely) from a location within the written spelling system.

Case 2

H.L. was a right-handed man with a high school education who, before retirement, worked as a bookkeeper and programmer for a construction company. He had a central scotoma in his left eye as a result of a macular artery occlusion; in addition, he had glaucoma in the right eye. At age 70, 1 year before the onset of this investigation, he suffered a cardiovascular accident during the course of a prostatectomy. At that time, computed tomography scans revealed evidence of an infarct involving the posterior left temporal and anterior and middle aspects of the peripheral left occipital lobe, with sparing of the medial aspect. A smaller, second ischemic infarct was present in the posterior left frontal region (see Figure 4). A neuropsychological evaluation at the time of the stroke revealed a moderate expressive aphasia and right hemiparesis. In addition, there was some indication that he also suffered a right visual field hemianopsia.

By the time of our investigation, his spoken skills had recovered such that his performance in the tasks of picture naming, sentence repetition, and comprehension were excellent. He exhibited marked difficulties in reading normalized text. These difficulties presumably were related to the retinal damage. Consistent with this was the observation that his naming of enlarged single letters was flawless. H.L. also exhibited impairments in both written and oral spelling. He was able to write with his dominant right hand; his handwriting was legible, and he was able to copy unfamiliar forms and draw objects on request (see Figure 3).

To examine H.L.’s spelling difficulties in greater detail, we administered a set of 740 words for both oral and written
spelling, following the procedures outlined for J.G.E. An examination of the error corpus indicated two deficits: One was reflected in the word-level errors and the other in letter-level errors. Erroneous responses were classified in the following way: If a target–error pair could be considered as a word-level error, it was scored as such; otherwise, it was coded as containing one or more letter-level errors. We did not include the category of mixed word/letter-level errors because it is not possible to unambiguously identify these. The proportions of word-level errors are reported as a function of the total number of words administered; letter-level errors are reported as a function of the number of letters administered.

As indicated in Table 2, H.L. did not make semantic errors but, in contrast to J.G.E., he did make a considerable number of PPEs (e.g., enough → ENOFF) in both output modalities. The large number of PPEs, in conjunction with his good comprehension of the words he misspelled, indicated a deficit affecting the orthographic output lexicon. Such a deficit would be expected to result in the application of POC procedures to those words that were unavailable in the orthographic store and thus should affect both written and oral spelling comparably. Consistent with this conclusion is the finding of significant effects of regularity and frequency in both written and oral spelling: Words with more predictable phonology–orthography mappings were spelled better than those with more irregular correspondences (90% vs. 66% accuracy), and high-frequency words were spelled better than low-frequency ones (80% vs. 65% accuracy).

H.L. also produced several visually or phonologically similar word responses in both output modalities. These were responses that were actual words of the language and that shared at least 50% of the target letters (e.g., excess → EXCEPT). These errors can be interpreted in many ways: They may represent a misperception of the stimulus on input (e.g., hearing die for tie), they may be the result of an impairment to the orthographic output lexicon itself whereby similar word forms are confused, or, in some cases, they may represent the misclassification of errors on our part. For example, in the case of DIE and TIE, the actual error may consist of a simple letter substitution that happens to result in an actual word. However, because there are a number of instances that are unlikely to have resulted from simple letter substitutions (e.g., excess → except), we decided to classify all real word errors as visually and phonologically similar words. What is important is that, in terms of word-level errors, H.L.’s performance across written and spoken spelling modalities was remarkably similar, \( x^2(3, N = 1,480) = 1.57, \) ns, as would be predicted by a deficit to a central level of representation such as the orthographic lexicon.

By contrast, we found marked modality-specific differences for letter-level errors (see Table 3), \( x^2(4, N = 6,646) = 35.04, p < .0001. \) These differences are particularly apparent in the number of letter substitutions: 106 in written spelling versus 18 in oral spelling. The disparity in performance across modality of output is crucial for establishing that the letter substitution errors (which cannot be classified as PPEs or visually and phonologically similar words) do not arise from a central modality-independent source such as the orthographic lexicon or the graphemic buffer. Therefore, we can be confident that these errors were, at least primarily, the result of a deficit to a processing stage that was further downstream and that was specific to the written spelling system.

We have established that both individuals had deficits affecting the written spelling system. Although H.L. had an additional central (presumably lexical) deficit, we were able to separate the errors arising from his lexical and postlexical...
impairments (see Goodman & Caramazza, 1986, for another individual with this same combination of deficits). To collect a larger corpus of substitution errors, we gave J.G.E. and H.L. additional lists of 4- to 10-letter words for written spelling only. J.G.E. produced 138 substitution errors (out of a total of 3,800 letters administered), and H.L. made 190 substitution errors (out of a total of 6,685 letters). These error sets were used in the subsequent analyses that we report.

**Visuospatial Versus Stroke-Feature Similarity**

Our basic assumption is that brain damage creates a situation in which representations that are similar to one another are confused. If we take similarity to mean overlap in some representational space, then our purpose in conducting these analyses is to gain some insight into the nature of the implicated representational space. We do so by comparing two hypotheses about the nature of the representations involved in the substitution errors produced by J.G.E. and H.L. The first, which we refer to as the visuospatial hypothesis, assumes that the representations involved in these errors consist of descriptions of the shapes of letters that do not involve information regarding the manner in which letters would be produced in writing. Presumably, such representations are similar to those used in the recognition of visually presented letters and are expressed in a visual-feature vocabulary. We contrast this with the stroke-feature hypothesis, according to which the representational level that forms the basis of the errors of these individuals involves a description of letter forms specifically in terms of the characteristics of the strokes required to produce the forms. One concern is whether stroke-feature and visual-feature vocabularies are equivalent or so similar as to be indistinguishable. This concern could be addressed directly if there were some consensus about theories of visual features, stroke features, or both. The difficulty, of course, is that there is enormous uncertainty regarding visual or motor feature vocabularies. There are, however, no a priori reasons to suppose that these vocabularies should be indistinguishable. Thus, although both presumably would include a basic feature set and a scheme for describing the relationships among features, it is not difficult to imagine that these might differ. Consider an E, for example. It is possible that a stroke-feature description might include the four strokes required to create the shape represented in terms of direction and orientation of movements, with the relationships among strokes represented in terms of points of attachment. By contrast, a visual description might include information about the contour, its general concavity, the three line terminations, the line junctions, and so on.

Thus, the problem we faced was the need for metrics for determining the extent to which target–response pairs produced by J.G.E. and H.L. were similar in terms of visuospatial characteristics or stroke features (or neither). Given the paucity of theory on which to based these metrics, we decided to pursue a strictly empirical approach in developing a visuospatial metric and a more intuitively driven approach with respect to the stroke-feature metric. As will become apparent later, we found that the two metrics we adopted do make different predictions about which pairs of letters should be more or less confusable. That is, we found letter pairs that were visuospatially similar but dissimilar in terms of stroke features (and vice versa). This is a clear indication that visuospatial and stroke-feature similarity can in fact be distinguished.

**Methods**

We describe the visuospatial similarity metric; the metric of stroke-feature similarity; and how, on the basis of the two, we coded each of the target–error pairs actually produced by J.G.E. and H.L. as being similar on neither measure, on both, on only the visuospatial metric, or only on the stroke-feature one.

**Visuospatial Similarity Metric**

We developed a measure of visuospatial similarity that was based on the actual errors of unimpaired individuals who are required to identify briefly displayed uppercase letters. Under such conditions...
describe stroke sequences. The arbitrariness of our feature selec-

tion among the many features that might be used to

more systematic exploration of the features involved in stroke

tion and the procedures we used to establish stroke-feature simi-

larity, we decided to make a relatively arbitrary, intuitively
t-based decision. This would render the normal letter confusion matrix

one that formed the basis of H.L.'s and J.G.E.'s letter-form rep-

resentations. This would make it possible to consider as visually similar

the four most common confusions

that shared its entire stroke-feature set (e.g.,

A-B, A-C, A-D, etc.) according to a simple dichotomous variable—similar or dis-

similar—on the basis of the probability of occurrence of each

collection. We coded the matrix three times using three different
cutoff levels for the dichotomous variable: 3%, 2%, and top 4. For

the 2% cutoff, each target-error pair that constituted at least 3% of

the responses for a given target letter was coded as visually similar,

whereas each pair that occurred in less than 3% of the trials for any

given letter was coded as dissimilar. The same procedure was

repeated at the 2% level. Finally, we also used a cutoff that

considered as visually similar

the possibility that letters with high overall accuracy rates would

have few target-error pairs with an incidence of 2% or 3% (e.g.,

L, with an overall accuracy of 94% had no confusions with an

incidence greater than 2%). The situation exemplified by L was a

relatively rare occurrence. A more typical example is the letter B,

which was identified by subjects at least 3% of the time as each of

the following letters: D, E, G, O, P, R, S, U. When a 2% cutoff

level was used, then, F, H, K, L, N, Q, V were added to the list.

When a "top 4" criterion was used, only G, R, D, E were coded as

visually similar. This procedure resulted in three separate metrics

of visuospatial similarity in which each possible letter pair was

coded as visually similar or dissimilar.

One could be concerned that the forms of the letters produced by

H.L. and J.G.E. in writing were highly dissimilar from those that

were presented by Gilmore et al. (1979). In such a case, one might

worry that H.L.'s and J.G.E.'s letter-form representations might

actually be visuospatially based but that the visuospatial similarity

space explored with the unimpaired individuals differed from the

one that formed the basis of H.L.'s and J.G.E.'s letter-form rep-

resentations. This would render the normal letter confusion matrix

irrelevant. However, Figure 5 reveals that the letter shapes pro-

duced by J.G.E. and H.L. were highly similar to those used by

Gilmore et al. (as well as to the forms used in a similar experiment

by van der Heijden, Malhas, & van den Roovaart, 1984, to which

we refer later).

Stroke-Feature Metric

Given the lack of either a theoretical or empirical precedent on

which to base our attempt to develop a metric of stroke-feature simi-

larity, we decided to make a relatively arbitrary, intuitively
driven selection among the many features that might be used to
describe stroke sequences. The arbitrariness of our feature selec-
tion and the procedures we used to establish stroke-feature simi-
larity certainly can be called into question, but they constitute a

starting point that, if promising, could provide the basis of future

more systematic exploration of the features involved in stroke

specification.

Figure 5. Examples of letters produced by H.L., J.G.E., H.E.,

and J.B. and the stimuli used in the experiments by Gilmore,

Hersh, Caramazza, and Griffin (1979) and van der Heijden, Mal-

has, and van den Roovaart (1984).

An initial decision was to exclude the characteristics of move-

ments that do not make contact with the paper and are involved in

placing strokes at their correct anchoring point (e.g., in making an

A, writers typically make an upward and then downward stroke

and then move off the writing surface to make a horizontal stroke

from left to right connecting the two previous strokes). Following

this basic decision, our coding procedure was as follows. In Step

1, we categorized each letter according to the number of strokes

J.G.E. and H.L. used to produce it: 1, 2, or 3+ strokes. We took a

stroke to correspond to a movement segment whose beginning and

corresponded either to points where the pen was lifted off the

writing surface or where lifting the pen off the writing surface

would not be considered to be an interruption. For example,

according to these criteria, T was produced with two strokes with

a pen lift after the vertical; B corresponded to 3 strokes with a pen

lift after the downward vertical and an optional pen lift after the

first semicircle. In Step 2, we then chose the following character-

istics to describe each stroke of each letter: shape (line or curve)

direction of lines (downward or upward) and curves (clock-

wise or counterclockwise). For lines only, we also coded the

orientation of lines (horizontal or vertical) and an additional fea-

ture that we call "offshoot" and that refers to whether a line was

anchored or attached to a vertical line (e.g., the lines anchored to

the vertical in a K, R, E, etc.). In Step 3, each letter was compared

with every other letter in the alphabet and was coded as being

similar in terms of stroke features in the following way: a 3+-

stroke letter was judged to be similar to another 3+-stroke letter if it

shared the features of 2 of the 3+ strokes (e.g., F-H); a 3+-stroke

letter was similar to a 2-stroke letter if it shared the features of both of the strokes (e.g., F-L). To be classified as

similar, 2-stroke letters had to share all the features of other

2-stroke letters (e.g., L-T) and two of three features of 3+-stroke

letters (e.g., D-R). A single-stroke letter was similar to any letter

that shared its entire stroke-feature set (e.g., C-D).

For example, we characterized the three strokes of B in the

following way: line-vertical-downward, curve-clockwise, and

curve-clockwise. Letters sharing two of these three stroke features

were P (l-v-dn, c-cw), D (l-v-dn, c-cw), and R (l-v-dn, c-cw,

l-offshoot). The only exception to this coding scheme was the


letter I, which both J.G.E. and H.E. typically (although not always) produced with a single downward vertical line. Given the large number of letters that contain a downward vertical, we decided that, of these, only T and L would be considered to be stroke similar to I. In addition, J, Q, X, and Z were not considered as target letters given the limited frequency with which they appeared in the stimulus corpus. When considered in terms of these stroke features, J.G.E. and H.L. used virtually identical stroke sequence sets in forming the uppercase letters of the alphabet.

**Application to the Error Data**

On the basis of the visual and stroke-feature metrics, we then classified each of the target–error pairs actually produced by J.G.E. and H.L. as being (a) unrelated by either visuospatial or stroke-feature metrics, (b) visuospatially similar only, (c) similar only in terms of stroke features, or (d) ambiguous (similar according to both visual and stroke-feature metrics). This classification of each target–error pair was repeated for each of the three cutoff levels of visuospatial similarity coding. This was necessary because the assignment of an observed target–error pair to one of the four categories depended on its classification as visually similar or dissimilar. For example, F–T is similar in terms of stroke features; however, although at the 3% cutoff level it was not classified as a visually similar pair, at the 2% cutoff F–T it was. As a consequence, in the 3% cutoff scheme F–T was coded as similar only in terms of stroke features, but in the 2% cutoff scheme it was considered to have both visual and stroke-feature similarity and therefore was coded as ambiguous.

**Results**

**Visuospatial Versus Stroke-Feature Similarity**

The proportion of errors of each of the four types, for each cutoff level, are reported in Tables 4 and 5. The results indicate that for both H.L. and J.G.E. and at each of the cutoff levels, a considerably larger number of errors were observed that were similar in terms of stroke features than in terms of visuospatial characteristics.

One might be concerned that our particular coding metrics provided for dramatically unequal opportunities of occurrence for the various error types. For example, a low rate of visuospatial errors would necessarily result from a coding metric that considered only a few of all possible (26 × 26) letter pairings as visuospatially similar. However, this was not the case. Table 6 shows the number of possible letter pairings in the various categories according to the three different cutoff schemes. Although the 2% classification scheme has twice as many possible visuospatially similar pairs as stroke-feature pairs, Tables 4 and 5 indicate that visuospatial similarity described only half as many of the observed errors as did stroke-feature similarity.

Before drawing conclusions from these results, it was still necessary to determine (a) chance level rates for the various error categories and (b) the extent to which the results might be tied to the particular visual confusion matrix used. We address each of these in turn.

We first evaluated the possibility that the observed rates for each category type could have resulted from the random association of target letters and errors. Imagine, for example, that when uncertain of the identity of a letter subjects have a tendency to produce Es and Bs for reasons totally unrelated to the characteristics of the target letter (e.g., letter frequency). Furthermore, if these particular letters happen to share stroke features but not visuospatial features with a large proportion of the letters of the alphabet, we would observe high stroke-feature and low visuospatial similarity rates. These rates, however, would not indicate a systematic relationship between target and error because they should be observed even with a random pairing of targets and errors.

To evaluate this possibility, we randomly re-paired target and error letters 1,000 times for each subject, and coded each of the resulting target–error pairs according to our classification scheme.

The results are shown in Figure 6. Comparable results were obtained with the three cutoff values, but we report the results obtained for classifications based on the 3% cutoff because it was the metric that provided for the most equivalent distribution of opportunities of occurrence of the error types (see Table 6). The results clearly show that for both J.G.E. and H.L. observed rates of visual errors (H.L. = 7.37%, J.G.E. = 10.14%) lie clearly within the chance region. By contrast, neither the observed rates of stroke-feature errors nor the observed rate of ambiguous errors was ever generated in 1,000 random re-pairings of the data.

A second issue concerned whether the results were related idiosyncratically to the particular visual confusion matrix we used. An examination of the relevant literature for an-

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**Table 4**

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<thead>
<tr>
<th>Percentage of Observed Target-Error Type According to the Criteria of Visuospatial Similarity for H.L.</th>
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<tbody>
<tr>
<td>Criterion</td>
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**Table 5**

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<th>Percentage of Observed Target-Error Type According to the Criteria of Visuospatial Similarity for J.G.E.</th>
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<tr>
<td>Criterion</td>
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**Table 6**

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<th>Number of Possible Target-Response Pairs in Each Category</th>
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<tr>
<td>Criterion</td>
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<td>2%</td>
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<td>Top 4</td>
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</table>
other matrix of uppercase letters based on a sufficiently large number of trials revealed one reported by van der Heijden et al. (1984). The visual display conditions used by these authors differed from those used by Gilmore et al. (1979) in that, whereas Gilmore et al. presented briefly displayed stimuli at fixation, van der Heiden et al. used a presentation location of 2.75° from fixation. Both groups adjusted exposure duration to ensure 50% accuracy. An application of a 3% criterion to the normal visual confusions reported by van der Heijden et al. (1984) also resulted in roughly equivalent opportunities of occurrence for the various error categories (visuospatial, n = 56; stroke feature, n = 58; and ambiguous, n = 34). When J.G.E.'s and H.L.'s errors were then recoded according to this new metric, we continued to observe results that were highly similar to those obtained on the basis of the Gilmore et al. matrix (see Table 7). That is, for both J.G.E. and H.L. there were greater numbers of stroke-feature errors than visuospatial errors. In addition, when the recoded data were subjected to 1,000 random re-pairings, H.L.'s 3% rate of visual errors again fell within the lower end of the randomly generated results (range = 3–14%), whereas his 38% rate of stroke-feature errors was never generated (range = 6–24%). For J.G.E. the visual error rate of 6% also fell well within the range of the randomly obtained results (range = 3–17%), whereas the 15% rate of stroke-feature errors was generated only twice in 1,000 re-pairings (range = 2–15%).

In summary, the results of these various analyses clearly indicate that both J.G.E. and H.L. reliably produced letter substitution errors that involved a type of target–error similarity that is better described in terms of a vocabulary of stroke features than in terms of the features involved in the visuospatial representations implicated in visual letter recognition. The finding held across a number of different classification schemes based on different empirically derived measures of visual similarity.\(^8\)

Effector Independence

That the errors consisted of other well-formed letters indicates that the problem is not likely to be one of motor control. However, the results described thus far do not specifically address the question of the level of abstractness of the affected representations. Thus, it would be important to collect positive evidence concerning abstractness by evaluating the effector dependence or independence of the implicated representations. To do so, we reasoned that if an effector-independent level of representation formed the basis of the observed errors, then the characteristics of errors produced by different limbs should be comparable. To examine this possibility, we tested H.L.'s left-handed writing extensively and also collected a smaller number of errors from letter drawing with his right foot. We did not test J.G.E. because he was only able to write with his left hand because of the right hemiparesis; furthermore, he was not tested with left-footed letter drawing or other subsequent tasks because he found these tasks extremely tedious and tiring.

H.L.'s left-handed writing was easily legible (see Figure 3), and we administered a total of 542 words for writing to dictation. We first compared his right- and left-handed performance on a subset of 137 words that were administered for both left- and right-handed writing. The results of

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\(^8\) If the reader is concerned that such findings are limited only to males, we mention that a female subject (S.B.) also has been extensively tested with exactly the same pattern of results (10% visuospatial errors, 21% stroke-feature errors, and 32% ambiguous errors). Her data are not reported in detail here because she suffered from an additional memory deficit that often caused her to forget the word that she was spelling; this made the report of the data more complex than for J.G.E. and H.L.
that comparison appear in Table 8. It is readily apparent that both word-level and letter-level error types were produced in comparable proportions for writing with either hand.

The additional lists that were administered for left-handed writing allowed us to collect a total of 127 left-handed letter substitution errors. These errors were coded according to the scheme described for right-handed errors. The results of the analyses are reported in Figure 7. This figure indicates that, as was the case for his right-handed writing, H.L.’s left-handed writing also resulted in a larger number of stroke-feature-related errors than visuospatial errors. In addition, the left-handed stroke-feature errors were produced at rates above those observed in 1,000 random re-pairings of targets and errors. In fact, a chi-square comparison of right- and left-handed errors across the four categories revealed no difference, $\chi^2(3, N = 328) = 1.38$, ns. These striking similarities between responses with the left and the right hands provide strong support for the hypothesis that the implicated representations encode sufficiently abstract information about the features of letter strokes that these representations serve as the basis for written spelling with either the right or the left hands.⁹

To evaluate the possibility that effector independence extends beyond the same limb type, we asked H.L. to draw single letters with his right foot. He was asked to produce single letters using his stockinged foot on the floor. The examiner observed and noted the strokes he used and was able to clearly identify the vast majority of his productions; these few with an ambiguous interpretation were excluded from the analysis. We collected a total of 16 errors using this procedure. Although the results are based on a small data set, they indicate (see Table 9) that the rate of target–error pairs bearing stroke-feature similarity was far greater than that for visuospatially similar errors, and, in fact, the observed 44% rate of stroke-feature errors was generated only once in 1,000 random re-pairings of targets and errors.

### Size Independence

It is typically hypothesized that abstract motor plans do not include movement features such as slant and absolute size, which are thought to be parameters that are inserted into the programs at later processing stages. Thus, the level of abstractness of the implicated representational and processing stages also can be evaluated by considering writing performance across different writing sizes. If we are correct in proposing that H.L.’s writing deficit arose at the level of the selection of abstract motor plans, then we should find the same pattern of results regardless of writing size.

To evaluate this possibility, we dictated a set of words to H.L. for right-handed writing. He was asked to write the words in uppercase between lines that were 5 in. (27.7 cm) apart. This represented an approximately 20-fold increase over his natural writing size. Using this procedure we obtained 68 letter substitution errors, which we coded as in previous analyses. The results in Table 9 indicate that the rate of errors sharing stroke-feature similarity was superior to that of visuospatially similar errors. Once again, although rates of visuospatially similar errors were well within the randomly generated range, we did not obtain the observed rate of stroke-feature similarity in 1,000 re-pairings of targets and errors.

### Other Modalities of Letter-Form Production

We briefly summarize two other tasks that H.L. was administered. H.L. was asked to spell 115 words (479 letters) by assembling rubber letters. According to Margolin (1984), allographic (or physical letter-shape code) representations are used in typing and word assembly as well as written spelling; thus, it would be interesting to determine whether H.L. would have similar difficulties in word assembly as he did in writing. However, aside from some phonologically plausible errors, H.L. made only 4 letter substitution errors (3 of which were immediately self-corrected). H.L.’s good performance on this task was similar to that of individuals described by Zesiger et al. (1994), Black et al. (1989), and Lambert et al. (1994) who performed flawlessly on typing or word assembly tasks.

In addition, H.L. was asked to create letter forms using whole and half toothpicks. We were curious to see whether form-related letter substitutions would be produced in a task such as this one, which could be thought to require knowledge of letter forms for production. H.L. made 5 of 78 errors on this task. According to the criteria described earlier, three of these ($Y \rightarrow X, L \rightarrow T, F \rightarrow E$) would be categorized as stroke-feature related, one ($D \rightarrow C$) as visually related, and one ($B \rightarrow C$) as unrelated. Although insufficient for statistical analyses, these data provide some indication that form-related substitution errors also may be produced in non-writing tasks.

### Summary

The analyses we have performed indicate that (a) a considerable proportion of the errors produced by J.G.E. and H.L. bear a general physical similarity to the intended target; (b) this similarity is apparently based (at above-chance levels) on the features of the component strokes of letters rather than on the characteristics of letters that un-

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⁹ The alternative hypothesis that H.L. suffered two comparable deficits at effector-dependent levels of representation cannot be ruled out, of course, but it is somewhat unlikely given the degree of similarity observed.
derlie visuospatial confusions; and (c) the implicated representations are independent of effector and size.

These findings constitute strong evidence for the existence of effector-independent representations dedicated to stroke-feature specification. We are not, however, claiming that there are only effector-independent representations of letter forms. The data we have presented do not address the possibility of an additional level involving the effector-specific representation of letter form. In fact, one way of interpreting the finding reported earlier (Zesiger et al., 1994) of form-related letter substitutions in left-handed but not right-handed writing would be to assume that there is a level of letter-form representation that is specific to each hand. However, one would not expect an effector-specific representational level to be identical to the earlier effector-independent one, so that, presumably, detailed error analyses should reveal representational distinctions between two such levels of letter-form representation. Alternatively, however, the pattern reported by Zesiger et al. (1994) could be understood as arising from a deficit specifically affecting the transfer or translation of intact effector-independent letter-form representations into left-hand motor programs; according to this interpretation, letter-form representations would be present only at an effector-independent level. Additional studies are required to disambiguate these possibilities.

Furthermore, we are not proposing that the specific stroke features we have chosen are the appropriate ones but simply that, in combination, they account for a significant portion of the target–error relationship. Almost certainly other features will do so more successfully. Further work is required to examine the particular stroke features that we have selected as well as others to develop a more accurate description of the vocabulary of abstract stroke-feature specification. However, an examination of these issues requires a far larger error corpus than the one we have obtained from H.L. and J.G.E. and thus must await future investigation.

Distinguishing Among Levels of Representation

In the introduction we proposed to examine the assumption that the functional architecture of the writing system can be described in terms of multiple and distinct representational types and processing components. Specifically, we proposed to evaluate the distinction between amodal graphemic representations and abstract representations of letter form. One type of evidence that would provide strong support for a componential view of this sort would be a demonstration that characteristics of processing and representation at one level are not evident at others. Here we consider individuals with deficits that have been localized to the level of the graphemic buffer versus the level of letter-form specification on the basis of a certain set of criteria. We then examine other aspects of their writing performance to determine whether the specific representational and processing differences that are hypothesized to exist at the two levels are in fact observed.

As described in the introduction, within the theoretical framework adopted, a deficit affecting the central, postlexical component referred to as the graphemic buffer (see Figure 1) should result in a strong degree of similarity in error rates and types in both the written and oral spelling of words and nonwords. In fact, the similarities observed in individuals with hypothesized damage to the graphemic buffer involve not only similar overall error rates but also similar distributions of error types: letter substitutions, deletions, additions, and transpositions. This detailed association of deficits is difficult to account for without appealing to a common source of damage. Within the framework we have adopted, the graphemic buffer is the only mechanism shared by both words and nonwords in both written and oral spelling. By contrast, the dissociation between impaired written and spared oral spelling performance (such as that exhibited by J.G.E. and H.L.) can be localized only to postbuffer processes dedicated to providing form to abstract graphemes. Thus, individuals can be ascribed different loci of impairment on the basis of the association or dissociation of their performance in the written and oral spelling of words and nonwords (for a discussion of the interpretation of associations and dissociations, see Caramazza & McCloskey, 1991).

Interestingly, because impairment at either level results in the production of letter substitution errors in written spelling, the written production of individuals with hypothesized damage at either of these levels superficially appears to be highly similar (see Table 10 for errors from H.L. and J.G.E. and two individuals with hypothesized deficits to the graphemic buffer). The apparent similarity notwithstanding, the two sets of errors are hypothesized to arise from damage affecting representationally distinct types. Specifically, representations at the level of the graphemic buffer consist of amodal graphemes without name, shape, or font. These graphemic representations are thought to be multidimensional entities that include, along with information about grapheme identities and their order, the consonant–vowel (CV) status of the graphemes and possibly information

<table>
<thead>
<tr>
<th>Word errors</th>
<th>Letter errors</th>
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<tbody>
<tr>
<td>Hand</td>
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</tr>
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</tbody>
</table>

Note. PPEs = phonologically plausible errors; Vis/phon = visually and phonologically.

Table 8
Number of H.L.'s Errors in Various Categories According to Writing Hand

PPEs = phonologically plausible errors; Vis/phon = visually and phonologically.
about their syllabic organization (see Caramazza & Miceli, 1989, 1990; Cubelli, 1991; Jonsdottir et al., 1996; Kay & Harley, 1994; McCloskey et al., 1994). Furthermore, the graphemic buffer is hypothesized to be a working memory component that is sensitive to the amount of information (length of stimulus word or nonword) that is held in memory while subsequent processes are engaged. By contrast, the postbuffer representations implicated in the cases of H.L. and J.G.E. (although abstract in the sense of being effector independent) are specifically involved in the assignment of letter form.

If this characterization of the two representational types is accurate, we should expect specific differences in the error patterns that result from damage to either of the two: (a) The target–error pairs produced by damage to the graphemic buffer should not bear the stroke-feature similarity revealed in J.G.E. and H.L.’s errors; (b) the target–error pairs produced by J.G.E. and H.L. should not exhibit the preservation of CV status; and (c) given that we have no reason to suppose that a memory process is implicated at the level of letter-form assignment, we might expect that stimulus length should play no role in the error rates of J.G.E. and H.L.

To examine these predictions, we obtained the corpora of the uppercase letter substitution errors of 2 subjects who had been ascribed deficits at the level of the graphemic buffer. One was L.B., an Italian-speaking, 64-year-old, right-handed, university-educated individual reported by Caramazza and Miceli (1990). L.B.’s error corpus consisted of 698 uppercase substitution errors. The other was H.E., an English-speaking, 62-year-old, right-handed, high-school-educated individual described by McCloskey et al. (1994). H.E.’s error corpus consisted of 176 uppercase letter substitution errors. Therefore, having two sets of subjects (L.B. + H.E. and J.G.E. + H.L.)10 with purportedly distinct loci of damage, we could evaluate whether the predicted representational distinctions would be supported.

### Stroke Feature Similarity

As Figure 5 indicates, the letter forms produced by L.B. and H.E. were similar to those of J.G.E. and H.L. Thus, all target–error pairs produced by H.E. and L.B. were coded according to the 3% classification scheme for H.L. and J.G.E. The proportion of errors in the four categories is reported in Table 11, which also includes J.G.E.’s and H.L.’s data to facilitate the comparison. It is apparent from simple visual inspection that, the predominant error category for the graphemic-buffer subjects was the category of unrelated target–error pairs: 62% and 63%, which contrasts with the respective 20% and 23% rates for H.L. and J.G.E.

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10 The two sets of subjects were well matched in terms of sex, handedness, and education; L.B. and H.E. were 10 years younger than J.G.E. and H.L. Clearly, however, we did not expect that representational distinctions such as those we were examining would vary with age.
Table 10

Examples of the Superficial Similarity of Errors Produced by Individuals With Different Hypothesized Loci of Impairment

<table>
<thead>
<tr>
<th>Subject</th>
<th>Target 1</th>
<th>Response 1</th>
<th>Target 2</th>
<th>Response 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.G.E.</td>
<td>NOSE</td>
<td>NOST</td>
<td>FENCE</td>
<td>FTANCE</td>
</tr>
<tr>
<td>H.L.</td>
<td>FLAG</td>
<td>ELAG</td>
<td>SKIRT</td>
<td>SKIPT</td>
</tr>
<tr>
<td>L.B.</td>
<td>RITO</td>
<td>NITO</td>
<td>SAPONE</td>
<td>SAMORE</td>
</tr>
<tr>
<td>H.E.</td>
<td>BEFORE</td>
<td>BEFOLE</td>
<td>SIMPLE</td>
<td>SIMTLE</td>
</tr>
</tbody>
</table>

That is, both L.B. and H.E. primarily produced errors that were unrelated in terms of our indexes of visuospatial or stroke-feature characteristics. Second, if we consider the distribution of the remaining error types we find that, whereas all 4 individuals produced comparable levels of visuospatially similar errors, L.B. and H.E. produced far smaller proportions of stroke-related and ambiguous errors than did J.G.E. and H.E. When L.B. and H.E.'s data were subjected to 1,000 random re-pairings (see Figure 8), we observed that the error rates in the visuospatial category fell well within the random range. However, in marked contrast with J.G.E. and H.E., L.B.'s and H.E.'s error rates for the stroke-feature category also were consistent with the randomly generated rates. A chi-square analysis of the distribution of errors across the four categories revealed no difference between J.G.E. and H.E., \( \chi^2(3, N = 328) = 1.38, n.s. \), but significant differences between L.B. and J.G.E., \( \chi^2(3, N = 836) = 165.5, p < .001 \), L.B. and H.E., \( \chi^2(3, N = 888) = 266.7, p < .001 \), as well as between H.E. and J.G.E., \( \chi^2(3, N = 314) = 62.7, p < .001 \), and H.E. and H.L., \( \chi^2(3, N = 366) = 79.5, p < .001 \).

Preservation of CV Status

Both L.B. and H.E.'s letter substitution errors were characterized by extremely high rates of preservation of CV status (e.g., for L.B., scadla \( \rightarrow \) SCANDA or famoso \( \rightarrow \) FAMESO; for H.E., special \( \rightarrow \) SPECIAN or positive \( \rightarrow \) POSTAIVE). For L.B. 99% of all substitution errors preserved the CV status of the target letter; for H.E. this rate was 90%. This striking characteristic formed the basis of Caramazza and Miceli's (1990) proposal that abstract graphemic representations include a specification of the CV status of each abstract grapheme. It was argued that these internally complex graphemic representations can be damaged such that grapheme identities can be affected but their CV status spared. This gives rise to the situation in which a consonant or vowel may be specified for a particular position within a word, although the identity of the grapheme is damaged. Presumably, a grapheme that is consistent with the CV specification is then assigned to the position, resulting in the observed substitution error.

An examination of the preservation of CV status in the substitution errors produced by J.G.E. and H.L. revealed a 73% rate for H.L. and a 59% rate for J.G.E. When we randomly re-paired (500 trials) the target letters and errors of the 4 subjects we found (see Figure 9) that for L.B. and H.E., the CV status preservation rates were dramatically above the randomly generated rates. In marked contrast, J.G.E.'s preservation rate was well within the random range, and H.L.'s was just slightly above. The slightly elevated rates for H.L. were, in all likelihood, attributable to the mixed word- and letter-level errors. Recall that H.L. also had a deficit that resulted in the production of PPEs. Some PPEs would not have been detected by our scoring scheme because some proportion also would have been subjected to letter substitution errors arising from the additional deficit at the level of graphic-motor planning. For example, if the lexical deficit resulted in the application of POC to the word _humid_ resulting in _HUMED_ and the subsequent impaired processes produced _H \rightarrow T_, then the response TUMED would not have been categorized as a PPE. As a consequence, the _H \rightarrow T_ as well as the _I \rightarrow E_ errors would then have been included in the corpus of letter substitution errors. In such a case, however, the preservation of the V status in the _I \rightarrow E_ error is related to the operation of the POC system and not to the structure of graphemic-motor plans.

Effects of Stimulus Length

As Table 12 indicates, neither J.G.E. nor H.L. exhibited effects of stimulus length when we calculated the probability of making an error on a letter based on the number of letters in the word. We used the letter as the unit of analysis, which means that words with multiple letter errors (copy \( \rightarrow \) GOBY) would contribute multiple errors (number of incorrect letters/total number of letters). In fact, both J.G.E. and H.L. were as likely to make an error on a letter when they were simply asked to write a single letter as when they were writing a seven-letter word.

By contrast, both L.B. and H.E. exhibited marked length effects, with error rates increasing with stimulus length (see Table 13). These rates were calculated as the proportion of words that contained at least one error (incorrect words/total words). With the latter measure, it is important to rule out the possibility that the increasing error rate results from the fact that longer words (by virtue of having more letters) simply present greater opportunities for errors to occur. We can see, however, that this could not have been the case because error rates increased far more rapidly than did stimulus length (e.g., error rates for eight-letter words were more than 15 times those for four-letter words).

Table 11

| Percentage of Errors in the Various Categories for Both Sets of Subjects |
|----------------|----------|-----------|----------|-----------|
| Subject       | Visuospatial | Stroke feature | Ambiguous | Unrelated |
| L.B.          | 12        | 2         | 23        | 62        |
| H.E.          | 9         | 11        | 18        | 63        |
| J.G.E.        | 10        | 30        | 37        | 23        |
| H.L.          | 7         | 37        | 36        | 20        |
REPRESENTATION IN WRITTEN SPELLING

Figure 8. Observed and randomly generated values for the various error categories for all 4 participants. max = maximum; min = minimum.

Summary

With this set of analyses, we tried to examine the legitimacy of a model of the spelling process that proposes specific and distinct representational types. We did so by considering 4 individuals with brain damage who made written spelling errors that were superficially similar but that have been attributed to representationally distinct, yet functionally proximal, cognitive components. The adequacy of the distinctions proposed by the model were tested by examining detailed predictions regarding error characteristics. All predictions were confirmed: (a) Stroke-feature similarity was not evident in errors originating from the graphemic buffer, although it was clearly evident in errors with a postbuffer locus; (b) the predicted contrast between the two sets of subjects in terms of preservation of CV status was observed; and (c) the effect of stimulus length that signaled the involvement of a memory component was notably absent in those individuals with postbuffer impairments. These results constitute strong support for the proposed distinction between amodal graphemic representations and abstract letter-form ones.

Discussion

Our examination of the written letter substitutions of 2 individuals with brain damage clearly supports the existence of a level of representation that specifies in an effector-independent manner the features of the strokes that are required to produce letter forms. In addition, the detailed analysis of the written substitution errors of 4 subjects with brain damage provides further support for the distinction between the amodal representation of graphemes and the effector-independent, motoric representation of letter forms. This set of results prompts a number of questions: (a) How do these observations of impaired performance relate to evidence from normal errors? (b) Where do the results leave claims about the specification of letter shape in a visuospatial, nonmotoric code? (c) What can be learned from considering the neural locus of the impairments? (d) What is the relationship between the representations and processes required for written letter production and those required for visual letter recognition? We address each of these questions.
effector-independent manner. The results they obtained re-
letter-level information must have been represented in an
hand at the time of the switch. If so, and given our limited
experience in left-handed writing, it can be assumed that
form the new letters must have been available to the left
incurred in switching to the new word set, then the infor-
mation; min = minimum.

Convergence of Evidence

Ellis (1982) noted that his own written substitution errors
were often visuospatially similar to the target letters. This is
an indication that normal substitution errors may resemble
the errors produced by J.G.E. and H.L., although specific
analyses have yet to confirm whether the target–error simi-
larity of normal errors is based on stroke features or visuo-
spatial features.11

There are findings in the literature on unimpaired subjects
that have been used to argue specifically for the effector
independence of letter-form representations. Wright and
Lindemann (1993) examined the performance of individuals
learning to write with their left hand. They evaluated
whether subjects incurred costs in terms of the fluency and
quality of their handwriting performance when they
switched word sets during left-handed training. Subjects
switched from left-handed writing of a word set made up of
a limited number of letters (which were, in turn, composed
of a restricted set of strokes) to left-handed writing of
another set of words composed of different letters but in-
volving no new strokes. The reasoning was as follows:
Given that the stroke set remained constant, if no cost is
incurred in switching to the new word set, then the infor-
mation regarding the combination of strokes required to
form the new letters must have been available to the left
hand at the time of the switch. If so, and given our limited
experience in left-handed writing, it can be assumed that
letter-level information must have been represented in an
effector-independent manner. The results they obtained re-
vealed no switching costs, and the authors concluded that
handwriting involves effector-independent representations
of letters. These results seem to support the basic claims
proposed here, although further work is required to be
certain of the exact extent of convergence.

Site of Lesion

The site of brain damage potentially could constitute an
independent source of information about the nature of the
implicated representations and processes. Thus, we might
be able to consider lesion sites and ask if they are consistent
with the level of representation assumed to be affected. Both
J.G.E. and H.L. had multiple loci of damage (see Figures 2
and 4): J.G.E. suffered from left occipital damage extending
to posterior temporal areas with evidence of older, smaller
infarcts affecting the right occipital lobe, supra and periven-
tricular white matter, and the left thalamus; H.L. suffered
primary damage to posterior left temporal areas, with dam-
age to the anterior and middle portions of the peripheral
occipital cortex as well as to a posterior left frontal site. In
terms of grossly defined brain areas, the 2 individuals in this
study were similar in exhibiting both occipital and posterior
temporal involvement. By contrast, H.E. suffered posterior
parietal damage and L.B. suffered damage to superficial and
deep parietal structures. Unfortunately, however, this infor-
mation cannot usefully constrain our hypotheses given that
a wide range of brain areas has been implicated in dys-
graphic disorders of various kinds (see Roeltgen, 1993, for
a review).12 It is worth noting, nonetheless, that none of
these individuals' lesions affects motor areas known to be

11 As indicated in the introduction, carrying out such analyses
presents a difficulty that is particularly acute in work with normal
errors. The difficulty is that when errors may originate from
multiple levels (such as is the case with written letter substitu-
tions), it is not straightforward to determine the locus of any given
error. For example, an analysis of normal substitution errors indi-
cating the absence of stroke-feature similarity could be interpreted
either as being inconsistent with the evidence reported here or,
alternatively, as indicating that a substantial proportion of the
normal substitution errors originated primarily from the
graphemic-buffer level. To overcome this problem, an independent
means of establishing the locus of normal errors must be devel-
oped. In cases of brain damage, the extent to which we are satisfied
with the localization of a deficit to a particular component or level
of processing determines the confidence with which we can as-
cume that the observed errors reflect the properties of a particular
representational level (see Caramazza & Miceli, 1990, for further
discussion).

12 Studies aimed at establishing brain–cognition relations by
using data from neurological damage typically examine the lesion
sites of numerous individuals with purportedly similar functional
deficits and try to establish correlated areas of damage. The ap-
parent discrepancies in mapping brain areas to functional deficits
undoubtedly result (at least in part) from the fact that a careful
determination of the functional locus of the errors typically has not
been carried out. Under those circumstances, a grouping of pa-
tients by superficial error characteristics is unlikely to yield con-
sistent findings. In addition, there may be considerable individual
variation in neural instantiation of function.
involved in the more peripheral aspects of motor execution and control.

One thing that is intriguing is the apparent occipital involvement in H.L. and J.G.E., as well as in other cases that report a physical resemblance between target and errors: Both the Lambert et al. (1994) and Black et al. (1989) subjects suffered left occipital–parietal damage, whereas Weekes's (1994) subject had multiple loci of damage resulting from a head injury that affected the right occipital, temporal and frontal, and left parietal lobes. The posterior areas that were affected in all of these individuals were association areas that are considered by some to play a critical role in visual–motor interface (Andersen, 1987). However, the significance (if any) of this posterior tempororooccipital involvement certainly requires further and more rigorous examination with larger numbers of carefully studied individuals.

What About the Visuospatial Representation of Letter Form?

In the introduction we argued that the available evidence does not require that we posit visuospatially based representations of letter shape such as those proposed by Margolin (1984) and Ellis (1982, 1988). Nonetheless, the evidence presented here regarding the effector-independent, motorically based representations of letter form does not, of course, rule out additional visuospatially based ones; it simply underscores the fact that there do not appear to be obvious computational or empirical reasons for a visuospatially based level of representation. Our analyses do point to the type of evidence that would support visuospatially based representations: a pattern of impairment in which target–error pairs reliably shared visuospatial characteristics.

Before continuing, we consider the possibility that we failed to find evidence of visuospatially based letter-form representations because of specific assumptions that we made about the writing process. One might argue, for example, that handwriting is based on "drawing" visuospatially based representations in the same way one might draw a remembered or imaged form. Thus, contrary to what we have assumed, there would be no preassembled, stored specifications of the stroke features corresponding to each letter; instead, stroke features would be assembled as needed. According to this scenario, the deficits exhibited by H.L. and J.G.E. could be described as deficits in explicitly deriving the stroke-feature sets required to create intended letter shapes. The problem that we see with this account is that it does not predict well-formed letter substitutions. That is, if there were a problem in translating visuospatially defined letter shapes into an appropriate stroke set, one would expect letters with missing strokes, strokes not pertaining to the letter, improperly attached strokes, and so on. Instead, J.G.E. and H.L. produced well-formed letter substitutions. This pattern of responding would seem to falsify such an account.

We are not, however, arguing that all written and drawing output is based on stored stroke-feature sets and motor plans, just the writing of highly practiced forms such as letters and digits. In fact, it is likely that other motor acts such as the drawing of familiar objects involves assembling stroke sets in a manner much like that described earlier. If this is correct, we would not expect individuals with deficits in the selection of letter-form representations necessarily to have difficulties in drawing. In this regard it is interesting that H.L. did not exhibit any difficulties in drawing and that although J.G.E.'s drawings were only barely adequate, this might, as noted earlier, have been due to the fact that he was drawing with his left hand or due to additional deficits.

### Relationship Between Recognition and Production

The previous point leads naturally to the question of the relationship between the knowledge of letter shape that is used in written production and that used in visual recognition. A number of different possibilities can be entertained, and, although we can only go a short distance in empirically distinguishing among them, it is useful to review them briefly.

One possibility is that abstract, motorically based representations are used by both visual recognition and motor production systems (see Figure 10A for a schematic depiction). In fact, such a proposal is in the spirit of motor-based theories of speech perception (Liberman & Mattingly, 1985). If we assume that the representational level implicated in J.G.E. and H.L.'s errors is a reasonable candidate for this shared structure, we can examine the hypothesis by considering J.G.E. and H.L.'s letter recognition abilities. According to the motorically based hypothesis, we should expect to see an association between writing and recognition impairments in these individuals.

Although J.G.E. was able to accurately copy letters (97% correct; n = 675), he exhibited considerable difficulty in naming the same letters (23% errors). He also had difficulty (78% accuracy; n = 125) matching letters across font (a and A) and case (A and a). His accurate copying reflects his

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### Table 12
Error Rates (Incorrect Letters/Total Letters) According to Stimulus Length

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.G.E.</td>
<td>3.8</td>
<td>4.3</td>
<td>4.6</td>
<td>3.9</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>H.L.</td>
<td>3.8</td>
<td>2.1</td>
<td>3.9</td>
<td>3.6</td>
<td>3.0</td>
<td>3.9</td>
</tr>
</tbody>
</table>

### Table 13
Error Rates (Incorrect Words/Total Words) According to Stimulus Length

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.B.</td>
<td>---</td>
<td>5.6</td>
<td>23.5</td>
<td>32.8</td>
<td>51.9</td>
<td>76.9</td>
</tr>
<tr>
<td>H.E.</td>
<td>0</td>
<td>3.4</td>
<td>10.4</td>
<td>17.0</td>
<td>25.7</td>
<td>54.6</td>
</tr>
</tbody>
</table>
accurate perception of the shapes of letters. Given his accurate naming of letters in oral spelling, we think that his difficulties naming visually presented letters and matching across case and font resulted from difficulties in generating abstract representations of letter shape and identity (see Rapp et al., 1993; and Leek et al., 1994, for more details). This might be taken as support for the motor-based view of recognition. However, if we compare the distribution of J.G.E.'s uppercase naming errors with his uppercase written errors (using the categories of ambiguous, visuospatial similarity, stroke-feature similarity, and unrelated), we find that the two distributions are clearly distinct, $\chi^2(3, N = 305) = 41.2, p < .001$.

Critically, H.L., in contrast to J.G.E., was 100% accurate ($n = 130$) in naming visually presented uppercase letters. Similarly, the Black et al. (1989) and Lambert et al. (1994) subjects, although we cannot be certain that they suffered from a functional writing deficit equivalent to that of J.G.E. and H.L., also had no difficulty in visual letter identification. The fact that a letter recognition deficit is not necessarily associated with a deficit affecting the abstract motoric specification of letter shape creates important problems for a motor theory of letter recognition. In light of these results, we take the recognition deficit exhibited by J.G.E. to be a functionally independent, fortuitously associated deficit.

Another possibility is that letter recognition and letter production are related by means of abstract visually based representations (see Figure 10B). Such an architecture might be similar to that proposed by Ellis (1982, 1988) and Margolin (1984). The type of evidence required to support the proposal as well as some of its shortcomings were discussed in the introduction.

A third possibility is that the mediation between perception and production is carried out by supra-shape representations that are neither visually nor motorically based representations of letter form (see Figure 10C). According to such a scheme, J.G.E.'s and H.L.'s writing deficits result from damage affecting stages subsequent to the supra-shape representations, whereas J.G.E.'s recognition deficit results from damage to stages prior to the supra-shape representations. Although certainly plausible, it is difficult to imagine what such shape representations would look like or what function they would serve.

Finally, there is an organization (see Figure 10D) according to which abstract visuospatial representations used in recognition are related to motorically based representations used in production via an amodal representation of graphemic identity (see Caramazza, Capasso, & Miceli, 1996). The same amodal representations also would mediate between spoken letter-name recognition and letter-name production. Some advantages of such a scheme are that it is consistent with the evidence that we have presented here (in contrast to the scheme shown in Figure 10A), it posits only representational types that have been independently motivated (in contrast to the scheme shown in Figure 10C), and it does not have the other unmotivated features of the scheme shown in Figure 10B that were discussed in the introduction.

In spite of certain advantages of the scheme shown in Figure 10D, it should be clear that the various hypotheses are sufficiently underspecified that it is not easy to determine which patterns of performance would be required to empirically distinguish among them. Further work in the area of letter recognition and production is certainly required.
Conclusion

In conclusion, we have interpreted the results reported here as providing evidence that the cognitive system responsible for written spelling includes an abstract, effector-independent stage at which letter forms are represented in a vocabulary of stroke features. Furthermore, this representational stage can be usefully characterized as distinct from an earlier one at which amodal graphemic information is specified. Our research is an example of how detailed aspects of the performance of individuals with brain damage can be interpreted within, and used to inform, a componentially based theory of written spelling.

References


