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What Do Letter Migration Errors Reveal About Letter Position Coding in Visual Word Recognition?

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Dividing attention across multiple words occasionally results in misidentifications whereby letters apparently migrate between words. Previous studies have found that letter migrations preserve within-word letter position, which has been interpreted as support for position-specific letter coding. To investigate this issue, the authors used word pairs like STEP and SOAP, in which a letter in 1 word could migrate to an adjacent letter in another word to form an illusory word (STOP). Three experiments show that both same-position and adjacent-position letter migrations can occur, as well as migrations that cross 2 letter positions. These results argue against position-specific letter coding schemes used in many computational models of reading, and they provide support for coding schemes based on relative rather than absolute letter position.

A key issue that must be addressed in any theory of visual word recognition is how to code for letter position: Without coding of position, it is not possible to distinguish anagrams like CAT and ACT. Although relatively little empirical work has been directed at assessing the relative merits of different letter coding schemes, the choice of coding scheme plays a central role in the performance of computational models of reading. The manner in which letter strings are coded determines the similarity between different letter strings, which consequently affects the ability to explain priming relationships and interactions among lexical competitors. The choice of input and output coding schemes also influences the difficulty of the learning process in computational models. A good illustration of this is provided by the development of parallel distributed processing (PDP) models of reading. The original Seidenberg and McClelland (1989) model used a contextual coding scheme (Wickelcoding) that dispersed spelling-to-sound regularities over a large number of local contexts. As a result, knowledge learned in one context did not apply in other contexts (e.g., learning the *k* → /k/ mapping in KING was irrelevant to learning the *k* → /k/ mapping in SKIN or MAKE). This hindered generalization, causing the model to produce implausible pronunciations of nonwords like KULP (Besner, Twilley, McCann, & Seergobin, 1990). Subsequent PDP models introduced revised coding schemes that enabled better generalization (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996). However, these revised schemes introduced other problems, which were in some cases even more serious, as described below. Theoretical problems of this sort can only be solved by choosing an appropriate letter coding scheme.

Position-Specific Coding Schemes

The most common solution to the problem of coding letter position is to assume the existence of position-specific letter units (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 1999; Hinton & Shallice, 1991; McClelland & Rumelhart, 1981; Plaut, 1999; Zorzi, Houghton, & Butterworth, 1998). This approach assumes that there are separate slots of position-specific letter codes (i.e., one slot for each possible letter position). For example, the word CAT is coded by activating the three letter codes C_1, A_2, and T_3, whereas the word ACT is coded as A_1, C_2, and T_3 (where the subscripts index letter position). This type of *slot-coding* approach is used in the interactive activation (IA) model (McClelland & Rumelhart, 1981), the dual-route cascaded (DRC) model (Coltheart et al., 2001), and the multiple readout model (MROM; Grainger & Jacobs, 1996), as well as some PDP models (Hinton & Shallice, 1991; Plaut, 1999).

Evidence Against Position-Specific Coding

However, there are a number of empirical phenomena that are incompatible with position-specific coding. One of these is the phenomenon of transposed letter (TL) confusability. TL pairs are pairs of letter strings that are identical save for the transposition of two adjacent letters (e.g., TRIAL–TRAIL). Several lexical decision experiments have found that responses to TL nonwords like WODNER (derived from the word WONDER) are slower and less accurate than responses to control nonwords like LODNET (Andrews, 1996; Chambers, 1979; Davis & Andrews, 2001; O'Connor & Forster, 1981). Interference effects have also been observed for

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TL words in a variety of tasks, including lexical decision (Andrews, 1996; Chambers, 1979; Davis & Andrews, 2001), naming (Andrews, 1996; Davis & Andrews, 2001) and semantic categorization (Taft & van Graan, 1998). Finally, a number of masked priming experiments have demonstrated the perceptual similarity of TL stimuli (Andrews, 1996; Forster, Davis, Schoknecht, & Carter, 1987; Perea & Lupker, 2003). For example, Forster et al. found that priming a word with an orthographically related TL nonword was just as effective as identity priming (e.g., anwser–ANSWER = ANSWER–ANSWER) and more effective than priming with a nonword that was a neighbor of the target (e.g., ansmer–ANSWER). The phenomenon of TL similarity imposes strong constraints on coding schemes. For example, consider a TL word pair like SALT and SLAT. Although these words have all four letters in common, only two of these letters (*S* and *T*) occur in corresponding serial positions. In this respect, SALT and SLAT are no more similar than SALT and SXXT, though these two pairs clearly differ in their perceptual similarity. Thus, explaining the effects of TL similarity is problematic for position-specific letter coding schemes.

Position-specific letter coding also has difficulty explaining cross-position priming effects. According to slot-coding schemes, priming effects should not be observed when the shared letters of the prime and target occupy different slots (e.g., PARSON should not prime SONIC). However, many priming experiments have shown that it is not necessary for primes and targets to overlap at absolute letter positions for priming effects to be obtained (e.g., De Moor & Brysbaert, 2000; Humphreys, Evett, & Quinlan, 1990; Jordan, 1986; Peressotti & Grainger, 1995, 1999; see also, e.g., Harris, 2001, for related cross-position effects observed in orthographic repetition blindness). For example, Jordan reported a lexical decision task with unmasked, short-lag primes, in which lexical decisions were facilitated by orthographically related word primes relative to unrelated word primes (e.g., SONIC was classified more rapidly when it was preceded by PARSON than when it was preceded by SECRET). Jordan concluded that this priming effect must have been due to orthographic overlap, because there was no semantic relationship between primes and targets, and a post hoc analysis showed that the magnitude of the priming effect was unaffected by whether the shared letter string was phonologically identical in the prime and the target (e.g., DETEST–TESTIFY) or phonologically distinct (e.g., LEGAL–GALA). The shared letters always occupied different positions in the prime and the target, and so this orthographic priming effect is difficult for position-specific coding models to explain. Another example of cross-position priming was reported by Peressotti and Grainger (1995), who combined a masked priming methodology with a letter–nonletter classification task. The target stimulus consisted of a trigram containing two *X*s and a remaining character that was either a letter or a nonalphabetic foil character (e.g., *$*, >); the participants' task was to determine if this character was a letter. For example, the correct response to the target XFX was "Yes," whereas the correct response to X$X was "No." The target was always preceded by a masked prime trigram that (a) contained the target letter in the corresponding position (e.g., FRT–FXX), (b) contained the target letter in a different position (e.g., TRF–FXX), or (c) did not contain the target letter (e.g., TRV–FXX). The results showed that targets were classified more rapidly when the target letter was present in the prime than when it was absent. Furthermore, facilitatory priming was observed even when the target letter occurred in different positions in the prime and target trigrams (e.g., TRF–FXX). The size of the priming effect depended on the degree of displacement (i.e., the priming effect was greater when the critical letter was displaced by one position in the prime than when the critical letter was displaced by two positions).

The above cross-position priming effects illustrate a more general problem with slot-coding schemes based on absolute letter position, which we refer to as the *alignment problem* (Davis, 2004). This problem arises whenever familiar patterns are presented in unfamiliar positions. For example, if the word BOOK is coded as a pattern consisting of the letter *B* in the first position, *O* in the second position, and so on, how is this word recognized when it occurs in a complex context like HANDBOOK? The difficulty of achieving position-invariant recognition, combined with behavioral evidence of TL similarity effects and cross-position priming, argues against the use of position-specific letter coding in models of reading (for more discussion, see Bowers, 2002).

Illusory Words Due to Letter Migration: Evidence for Position-Specific Coding?

There is, however, a phenomenon that has often been cited as strong evidence for the existence of position-specific letter units. For example, Hinton and Shallice (1991) commented that "psychological evidence compatible with the existence of [position-specific letter] units can be obtained from the study of migration errors" (pp. 78–79). The migration errors to which Hinton and Shallice referred typically occur when attention is divided across multiple words. For example, when the pair of words SAND and LANE are presented very briefly, followed by a pattern mask, the observer may sometimes report a blend of the two words, such as "sand sane" or "land lane."

The first experimental demonstration of this phenomenon was reported by Allport (1977). He used a visual masking display in which participants were tachistoscopically presented with a rectangular array of four words. Allport's goal was to induce semantic errors (e.g., DOG → "cat"). What he found, though, was that the most common types of error responses were *segmentation errors*, in which participants combined the letters of two or more words to form an illusory word. At around the same time, Shallice and Warrington (1977) reported similar errors in the responses of participants with attentional dyslexia to unmasked stimuli. For example, the patient F.M. read the pair of words WIN FED as "fin fed". In participants with and without acquired dyslexia, there was a strong tendency for letter migrations to preserve within-word letter position. For example, when two of the briefly presented words were HARK and WARD, Shallice and Warrington's participants would sometimes report the illusory word "hard," but not "dark" (which would require the letter *D* to migrate from the final position to the first position). This suggests that the between-word location of letters may sometimes be confused under pattern-masking conditions (or by acquired dyslexia patients) but that within-word location is preserved under these conditions.

The finding that letter migrations tend to preserve within-word position has been taken by several authors as support for the notion of position-specific letter units. The above quotation from Hinton and Shallice (1991) is one example; similar conclusions have also been drawn by other authors, for example:

> Because within-word migrations and migrations to non-corresponding letter positions are probably rare, one might want to make the additional assumption that each letter position in a word defines a separate dimension. Thus, confusions may arise between letters in corresponding positions of two words (two features within the same dimension) but not between two letters in a single word (features in different dimensions). (Mozer, 1983, pp. 532–533)

> A type of error made by normal subjects when arrays of words are presented briefly also demonstrates positional coding. . . . The point about these [letter migration] errors is that *letters will only migrate perceptually if they can maintain the same within-word position* [italics added] in the error as in the target word from which they originate. (Ellis, Flude, & Young, 1987, p. 457)

The dimensions referred to by Mozer correspond to the separate slots for each letter position in slot-coding schemes. Similarly, Ellis et al. interpreted letter migration errors as support for a scheme in which letter units are marked as corresponding to specific serial positions (e.g., C_1, A_2, T_3).

The idea that letter migration errors provide a window on the basic units underlying visual word recognition can be compared with the way in which illusory conjunctions have been argued to reveal aspects of the nature of basic perceptual features (e.g., Treisman & Schmidt, 1982). In both cases, brief presentation of stimuli may lead to features of one object being combined with those of a different object (e.g., a red square and a green circle may produce the percept of an illusory red circle). It is commonly assumed that attention plays a critical role in integrating these features (e.g., Treisman & Gelade, 1980). This attentional binding mechanism is disrupted when attention must be distributed over multiple, briefly presented stimuli or when brain damage affects the mechanisms of spatial attention (e.g., Shallice & Warrington, 1977).

An Alternative Explanation of the Position-Preservation Effect in Letter Migration Errors

The phenomenon of preservation of letter position in letter migration errors has been seen as providing fundamental insights into the nature of letter coding in the visual word recognition system. However, the implication that has been drawn from this phenomenon—that letter coding is position specific—appears to be at odds with other evidence, which supports a more flexible form of position coding. For this reason, it is important to consider whether the preservation of letter position in letter migration errors could have an alternative explanation. Consideration of the stimuli that have been used in previous letter migration experiments suggests a straightforward explanation. For example, consider a word pair like LIVE–LONE. The internal letters can migrate to the corresponding positions of the other word to form illusory words (i.e., LOVE, LINE). However, these letters cannot migrate to other positions without violating lexical constraints (i.e., producing a nonword) and graphotactic constraints (i.e., producing an illegal letter string like LVNE). Not surprisingly, participants in perceptual identification experiments are reluctant to produce responses that violate graphotactic and/or phonotactic constraints. They are also biased against violating lexical constraints; that is, participants are strongly biased toward producing responses that are words, even when they know that half of the stimuli are nonwords (e.g., McClelland & Mozer, 1986). Previous studies have not made any attempt to overcome lexical and graphotactic constraints on potential letter migrations, and it is therefore possible that these constraints are entirely responsible for the tendency of migrating letters to preserve serial position. This would imply that the strong conclusions that have been drawn about coding of letter position on the basis of letter migration errors are ill-founded. For this reason, it is necessary to determine whether letter migration errors do indeed preserve letter position when lexical and graphotactic constraints are relaxed.

Experiment 1

If the relative rarity of letter migrations between noncorresponding positions is due to a combination of lexical and graphotactic constraints, rather than an inflexible position-specific coding scheme, there is no reason why noncorresponding letter migrations should not be observed for appropriately designed word pairs. For example, consider the word pair STEP–SOAP. In this example, the letter *O* in the second position of SOAP can potentially migrate to the third position of the word STEP to form the illusory word STOP. This does not violate any lexical or graphotactic constraints, and hence one should expect to observe migrations for this pair if the usual position-preservation phenomenon is due to these constraints. However, if letter migrations preserve position because letter codes are position specific (separate *dimensions*), then migrations of the above form should not be observed. The purpose of Experiment 1 was to test these competing predictions.

Method

Participants. Twenty undergraduates from Macquarie University, Sydney, New South Wales, Australia, participated in the experiment. They received payment for participating in this and a series of other experiments. All participants were native speakers of English.

Stimuli and design. A partial-report methodology was used in which participants were shown a pair of words, followed by a cue that indicated which of the two words to report (e.g., Mozer, 1983). In the following, we refer to the cued word as the *target* and the noncued word as the *context*; in descriptions of word pairs, the target word is italicized (e.g., *STEP* SOAP), although of course the targets were not in italics when presented to the participants. Stimuli were constructed by selecting triples of four-letter words that had the same initial and final letters. One of these words was the target, and the other two were context words. The migration context word was selected such that one (and only one) of its internal letters could replace an internal letter of the target word to form a legal word. The control context word was selected such that neither of its internal letters could replace an internal letter of the target word to form a legal word.[1] For example, in the case of the target word *STEP*, the migration context was SOAP (in which the letter *O* can migrate to the third position of the target word to create the illusory word STOP), and the

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[1] In a few cases, a letter from the control context could migrate to the target to form a very low-frequency word (e.g., *MUTE* MERE → “mete,” *WIRE* WAKE → “ware”), although these illusory words were never reported. In any case, this does not affect the validity of our control contexts, which were designed simply to measure the frequency with which the designated letter migration responses occur in cases in which the migrating letter is not present in the context.

control context was SNAP (in which neither *N* nor *A* can migrate to the target to form a legal word). The inclusion of control contexts allowed us to determine how often the target word was misreported as the migration word when there was no possibility of a letter migration. For example, a report of "stop" in response to the trial *STEP* SOAP is potentially due to a letter migration, whereas a report of "stop" in response to the trial *STEP* SNAP could not possibly be due to a letter migration (because the critical letter *O* is not contained in the context). Responses of the latter form are referred to as *pseudo*- letter migration (LM) responses. Subtracting the number of pseudo-LM responses in the control context condition from the number of LM responses in the migration context condition enables us to measure the true rate of LMs.

In half of the migration context words, potential migrations were between corresponding letter positions in the context and target words (e.g., *SKIP* SHOP could produce the illusory word SHIP). In the other half, potential migrations were between adjacent letter positions (e.g., *STEP* SOAP → STOP). The serial position of the migrating letter was also manipulated: In half of the migration contexts, the second letter was the critical letter, whereas the third letter was the critical letter in the other half of the stimuli. Thus, the design involved an orthogonal manipulation of three binary factors: (a) type of context (migration vs. control), (b) same- versus adjacent-position migrations, and (c) serial position of migrating letter (Position 2 or 3). Table 1 shows examples of the stimuli. The full set of experimental stimuli for all of the experiments reported in this article can be found in Appendix A.

Procedure. Participants were tested individually in a quiet room. They viewed the screen binocularly from a distance of 57 cm; head position was fixed by a chinrest. Participants were told that they would see two words, followed by a cue that indicated which of the words to report. They were also told that words could appear more than once over the course of the experiment. The instructions stressed response accuracy rather than speed. There was a block of 30 practice trials before the experiment proper began. The stimuli for these trials were selected subject to the constraint that none of the letter combinations formed by combining the initial and final letters of a word in the practice trials could match an initial–final letter combination from the experimental stimuli; for example, the experimental stimuli included the trial *STEP* SOUP, and hence none of the words in the practice trial began with an *S* and ended with a *P*.

The sequence of events was as follows. A fixation point appeared on the center of the screen for 1,000 ms, followed by a blank screen for 500 ms. A pair of words was then displayed for a controlled duration (see below). The words were centered on the screen, separated by one character width (0.3°; i.e., the blank space was in the same physical position where the fixation point had previously appeared). The total width of the word pair subtended a visual angle of ~3.3°, while the height was ~0.4°. The letters of the two words were then replaced by a row of mask characters, which consisted of a plus sign (+) superimposed on a circle. The mask extended across a visual angle of 4.1°. After 200 ms, the mask disappeared, and a cue consisting of a horizontal line appeared 1° below the position where the target word had previously appeared. The participant then reported the identity of the probed word to the experimenter, who recorded the response and scored it as either correct or incorrect. The experimenter then pressed a key to commence the next trial. Participants were allowed to take a short break halfway through the experiment. Each participant saw each of the target words twice: once paired with a migration context and once paired with a control context. Four separate stimulus lists were prepared to counterbalance order of presentation (migration context first or control context first) and target position (left or right); each participant saw only one of these four lists. The order in which trials occurred was randomized, subject to these counterbalancing constraints.

The stimulus exposure duration on each trial was determined using a titration procedure that sought to produce an overall error rate of 30.0%. The initial exposure duration of the word pairs was 86 ms. After each block of 10 trials, the duration was adjusted in increments or decrements of one *tick*, with a tick corresponding to the screen refresh rate of the computer (14.33 ms). If the number of errors the participant had made on that block was less than three, the exposure duration was decremented by one tick, whereas if the number of errors was greater than three, the exposure duration was incremented by one tick. This procedure resulted in a mean exposure duration over all trials of 96 ms, with a range across participants of 32–220 ms.

Results and Discussion

The titration procedure was successful in controlling the error rate at a level close to 30.0% (the overall error rate was 31.3%). Accuracy of report was significantly greater for targets presented on the right ($M = 73.8\%$) than for targets presented on the left ($M = 63.5\%$), $F_1(1, 19) = 5.76$, $p < .05$; $F_2(1, 59) = 23.71$, $p <$

Table 1
Examples of Stimuli Used in Experiments 1–3

Experiment and position condition	From → to position	Target word	Similar contexts		Dissimilar contexts		Migration word
			Migration	Control	Migration	Control	
1							
Same	2 → 2	COPE	CAGE	CUBE			CAPE
	3 → 3	PINE	POPE	POSE			PIPE
Adjacent	3 → 3	CLIP	CAMP	CROP			CLAP
	3 → 2	LIMP	LEAP	LOOP			LAMP
2							
Same	2 → 2	COPE	CAGE	CUBE	VAIN	BUZZ	CAPE
	3 → 3	PINE	POPE	POSE	COPY	ROSY	CAPE
Adjacent	3 → 3	CLIP	CAMP	CROP	TASK	DRUG	CLAP
	3 → 2	LIMP	LEAP	LOOP	GOAT	FROG	LAMP
3							
Same	2 → 2	SMACK	SHARK	SPARK			SHACK
	4 → 4	SHAME	SCARE	STAGE			SHARE
Adjacent	2 → 3	BENCH	BATCH	BOTCH			BEACH
	4 → 3	BLOCK	BLEAK	BLINK			BLACK
Distant	2 → 4	CHANT	CRAFT	COAST			CHART
	4 → 2	ABIDE	ARISE	AGILE			ASIDE

.001. This is consistent with the standard right visual field (RVF) advantage for briefly presented word stimuli (e.g., Mishkin & Forgays, 1952). This RVF advantage probably reflects the dominance of the left hemisphere for linguistic processing, although it may also be due in part to the asymmetry of the perceptual span around the fixation point (e.g., McConkie & Rayner, 1976).

Each response was categorized as a correct response, an LM, a pseudo-LM, a word migration (WM), a pseudo-WM, or an *other* error. Note that LM responses can only occur for migration contexts, whereas pseudo-LM responses can only occur for control contexts. Table 2 shows the percentages of responses falling into each of these five response categories, broken down by context condition.

LMs. Overall, there were 53 LM responses and 14 pseudo-LM responses. The difference in the incidence of LMs and pseudo-LMs was highly significant, $F_1(1, 19) = 27.29$, $p < .001$; $F_2(1, 58) = 12.51$, $p < .001$. This indicates that although the number of LMs was relatively small, the methodology was successful in inducing genuine LM responses. The frequency of LM and pseudo-LM responses did not vary as a function of the target's position (left or right of fixation), $F_1(1, 19) = 1.05$, $p > .30$; $F_2(1, 59) = 1.27$, $p > .30$. Table 3 shows the percentages of LM and pseudo-LM responses in the same-position and adjacent-position conditions. As can be seen, in both conditions the number of LMs significantly exceeded the number of pseudo-LMs. Furthermore, the number of true LMs involving migrations between corresponding letter positions was similar to the number of true LMs between noncorresponding letter positions; the difference between these conditions did not remotely approach significance, $F_1(1, 19) = 0.11$; $F_2(1, 58) = 0.07$. Thus, not only was it the case that LMs did occur between noncorresponding letter positions (as predicted), but such migrations occurred just as frequently as those between corresponding letter positions. This constitutes strong evidence against position-specific letter coding.

WMs. The high incidence of whole WMs was rather unexpected. The only other experiment that we are aware of that has previously noted this phenomenon was Experiment 3 of Mozer (1983). In that experiment, WM responses were observed on 4% of trials in a divided-attention condition, in which participants had to first report the identity of two digits that flanked the words; WMs did not occur in the no-digit condition. Thus, the presence of WMs on 8% of trials in the present experiment might be taken as an indication that our participants found the task highly attentionally demanding. One reason that the present task may have imposed a higher attentional burden than did Mozer's experiments is that the duration times were, on average, much shorter. For example, in Mozer's Experiment 3, the average duration was 428 ms in the digit condition and 229 ms in the no-digit condition; by contrast, the average exposure duration in the present experiment was only 96 ms.[2]

Table 2
Breakdown of Percentages of Response Types for Migration and Control Contexts in Experiment 1

Response type	Context Migration	 Control
Correct	66.4	70.9
LM/pseudo-LM	4.4	1.2
WM	8.5	7.3
Pseudo-WM	0.3	0.2
Other	20.3	20.5

Note. LM = letter migration; WM = word migration.

Table 3
Percentages of Letter Migrations (LMs) for Same-Position and Adjacent-Position Conditions in Experiment 1

Position condition	LM	Pseudo-LM	Difference	p^a
Same	4.8	1.3	3.5	.008
Adjacent	4.0	1.0	3.0	.001

[a] Significance level of test (over participants) comparing frequency of LMs and pseudo-LMs.

Given the relative infrequency of single LMs, it is very unlikely that WM responses reflect double LMs. It is also unlikely that WMs are simply the result of word misidentification. By analogy with LM errors, the incidence of WMs can be compared with the frequency of pseudo-WMs (i.e., responses that correspond to the context word that is presented with the other occurrence of the target). For example, the target *STEP* was presented once with the migration context SOAP and once with the control context SNAP. Thus, in the case in which the target–context pair is *STEP* SOAP, a WM response would be SOAP, whereas a pseudo-WM response would be SNAP. There were only six pseudo-WM responses in all (0.25%), compared with 189 WM responses (7.88%). It is therefore clear that the relatively large number of WM responses cannot be ascribed to simple identification errors. Other analyses showed that the frequency of WMs did not vary as a function of context type (Fs < 1) or position condition (ps $> .25$).

Other errors. The most common types of errors were responses that did not correspond to either the target, the migration response, or either of the context words. These other errors were mostly words (96%) and were usually orthographically similar to the target (84% of the other responses contained at least two letters from the target; a large proportion of these responses were orthographic neighbors of the target, e.g., *WIRE* WAKE → "wide"). Other errors occurred significantly more often for targets that appeared to the left of fixation than for targets presented to the right of fixation, $F_1(1, 19) = 6.04$, $p < .05$; $F_2(1, 59) = 18.89$, $p < .001$ (this effect underlies the above-mentioned effect of target position on accuracy). The frequency of other responses did not differ between the migration and control contexts ($F < 1$).

In summary, Experiment 1 successfully replicated the phenomenon of LMs in a divided-attention paradigm. The critical result was the observation of LMs that crossed letter positions. Indeed, these adjacent-position LMs occurred just as often as those that preserved letter position. An unexpected aspect of the results was

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[2] In both experiments, exposure durations were varied to meet a 70.0% accuracy criterion. The discrepancy in mean exposure durations presumably reflects both participant-population factors and display characteristics of the stimuli (Mozer's, 1983, stimuli were presented in red with narrow spacing, preceded by a red rectangle that may have produced metacontrast).

the relatively large number of whole WMs, in which participants reported the context word instead of the target word. Although WMs are an interesting phenomenon in their own right, they are not directly relevant to the present questions concerning coding of letter position, and hence we do not pursue the cause of these errors here. Further discussion of this phenomenon is delayed until the General Discussion.

Experiment 2

One of the key facts concerning LM phenomena is the *surround-similarity effect*: The likelihood of combining letters from different stimuli in the display to form an illusory word depends on the similarity of these stimuli. In an experiment involving full report of four-word displays (e.g., HARK–WARD–LIVE–LONE), Shallice and McGill (1978) found that LMs were significantly more likely to occur between pairs of similar words (e.g., HARK–WARD → "hard") than between pairs that were mutually dissimilar (e.g., LONE–WARD → "word"). In two separate experiments involving partial report of two-word displays, Mozer (1983) found that LMs occurred for similar target–context pairs (like *STEP* and SHOP) but not for dissimilar target–context pairs (like *STEP* and FROG). Finally, McClelland and Mozer (1986) manipulated the similarity of target–context pairs in an experiment in which participants had to report the identity of a single cued letter. They replicated the effect of surround similarity on the frequency of LM errors (the estimate of true LMs was 14.5% for the similar contexts, compared with 6.5% for dissimilar contexts).

The surround-similarity effect has important implications for the locus of LM phenomena. The descriptor *letter migration* implies that the locus of the effect is at the letter level (i.e., that letters in briefly presented letter strings have a tendency to drift to different locations). Treisman and Souther (1986) favored this account of the phenomenon. In their feature-integration account, focal attention is required to localize letters—prior to this, letter identities are free floating, allowing letters to be recombined incorrectly to form illusory words. Therefore, if letter units are coded for serial position, letters can migrate between but not within words.

However, the feature-integration account of LM phenomena is insufficient to explain the effect of surround similarity. For example, if LMs are simply due to free-floating letter identities, the migration response "stop" should occur just as often for the dissimilar target–context pair *STEP* FROG as for the similar pair *STEP* SHOP; in either case, a failure of focal attention will allow the letter *O* to migrate between words. To explain the surround-similarity effect within this framework, it is necessary to incorporate an explanation of why letters are more likely to drift between orthographically similar words. One possibility is that target–context similarity increases the likelihood of the two stimulus words merging to form a single episodic perceptual trace (Treisman & Schmidt, 1982). However, the surround-similarity effect does not depend on physical similarity: In particular, case differences (step–ShOp or step–SHOP) do not affect the LM rate (McClelland & Mozer, 1986; Shallice & McGill, 1978). Furthermore, McClelland and Mozer found that surround similarity was not associated with a greater occurrence of migrations when letters were surrounded by digits (e.g., 2A22–2B22 is not more likely to produce LMs than 2A22–7B77). These findings are problematic for the feature-integration account of LM phenomena.

The surround-similarity effect can be explained more satisfactorily by positing a later, lexical locus of LM phenomena. Independent models along these lines have been proposed by McClelland and Mozer (1986). According to the lexical account of LMs, the tendency to report illusory words stems from the fact that the letters of both the target and context words converge on the representation of the illusory word; for example, given the word pair *STEP* SHOP, both stimuli partially activate the representation of the word STOP. By contrast, in the case of a dissimilar target–context pair like *STEP* FROG, the context word does not support the "stop" response, and so true LMs will not occur. The lexical account of LM phenomena also explains why there is no surround-similarity effect for letters surrounded by digits (given that stimuli like 2A22 are not lexically represented) and why case differences do not affect the likelihood of LMs. Thus, the available evidence supports the lexical account of LM phenomena. This suggests that the phenomenon known as *letter migration* might more aptly be referred to as *word conflation*. It is worth noting, though, that the LM errors of attentional dyslexic readers do not exhibit the same dependence on surround similarity (e.g., Mayall & Humphreys, 2002), which may suggest that these errors have a different (presumably earlier) locus in attentional dyslexia (Davis & Coltheart, 2002).

Nevertheless, the surround-similarity effect warrants further scrutiny. The results reported to date differ as to whether surround similarity is necessary for true LMs to be observed. Mozer (1983) observed a true migration rate of 11.0% with similar contexts (e.g., *CAPE* CONE), compared with a nonsignificant number of true LMs (less than 1.0%) with dissimilar contexts (e.g., *CAPE* MONK). By contrast, McClelland and Mozer (1986) reported a reasonably high percentage (6.5%) of true LMs when the target and context words shared no letters (e.g., *LAMP* HINT). The present experiment aimed to test for a surround-similarity effect in a single experiment, using a fixed exposure duration and the same partial-report methodology as Mozer. It is also of theoretical interest to determine whether the cross-position LMs and WMs observed in Experiment 1 are subject to surround similarity. If cross-position LMs occur for dissimilar target–context pairs, they may have a different cause than same-position LMs.

Thus, the goals of Experiment 2 were to (a) attempt to replicate the findings of Experiment 1, (b) further explore the surround-similarity effect, and (c) investigate the nature of LMs and WMs in further detail. By examining the effect of target–context similarity on LMs, we hoped to determine whether the cross-position migrations observed in the first experiment are best viewed as resulting from the tendency of letters to drift both between and within words or as the consequence of word conflation.

Method

Participants. Twenty undergraduates from the University of Bristol, Bristol, United Kingdom, participated in the experiment in return for course credit. All were native speakers of English.

Stimuli and design. The design of this experiment was similar to that of Experiment 1, with the introduction of the additional factor of context similarity (similar vs. dissimilar). The stimuli in the similar context conditions were the same 60 target–context triplets used in the first experiment. Dissimilar contexts for these targets were selected so that they shared no letters with the target but shared the critical letter with the corresponding similar context. For example, in the case of the target *COPE,* the similar migration-context item was CAGE, and the dissimilar migration-context item was VAIN (in both of which items the letter *A* can migrate to the second position of the target to create the illusory word CAPE), whereas the control-context items were CUBE and BUZZ, respectively (in which the internal letters cannot migrate to the target to form a legal word). For both the similar and dissimilar migration-context items, half of the potential migrations were between corresponding letter positions, and half were between adjacent letter positions. As in Experiment 1, the serial position of the migrating letter was manipulated: In half of the migration contexts, the second letter was the critical letter, whereas the third letter was the critical letter in the other half of the stimuli. Thus, four factors were orthogonally manipulated: (a) type of context (migration vs. control), (b) same- versus adjacent-position migrations, (c) serial position of migrating letter (Position 2 or 3), and (d) context similarity (similar vs. dissimilar). Each participant saw each of the targets four times: once with the similar migration context, once with the similar control context, once with the dissimilar migration context, and once with the dissimilar control context, for a total of 240 trials. Examples of the stimuli can be seen in Table 1. Items within a file were presented in a random order, and target position (left or right) was varied across two versions of the experiment.

Procedure. Participants were tested in groups of up to 4 in a quiet room. Each participant viewed a computer monitor from a distance of approximately 60 cm. As before, participants were told that they would see two words, followed by a cue that indicated which of the words to report, and that words would appear more than once over the course of the experiment. The instructions stressed response accuracy rather than speed. There was a block of 20 practice trials before the experiment proper began. As in Experiment 1, the stimuli for the practice trials were selected so that their initial–final letter combinations did not match those among the experimental stimuli.

The sequence of events on each trial was similar to that in Experiment 1. A fixation point appeared on the center of the screen for 1,000 ms, followed by a blank screen for 500 ms. A pair of items typed in uppercase font was then displayed for 71 ms to all participants (five refresh cycles at 14.2 ms each). The items were centered on the screen, separated by one character width. The items were then overwritten by a row of four number signs (####) presented for 200 ms, after which a cue consisting of a straight line appeared 1° of visual angle below the position of the target. The participant attempted to report the target by typing his or her response and then pressed the space bar to commence the next trial.

Results and Discussion

As in Experiment 1, responses were categorized as correct, LMs or pseudo-LMs, WMs or pseudo-WMs, or other errors. The proportion of responses falling into each of these categories for the various similarity and context conditions can be seen in Table 4. Unlike in Experiment 1, there was no attempt to control accuracy rates in the present experiment by varying target duration for each participant, and mean accuracy was somewhat lower in this experiment (60.0%) than in the former experiment (68.7%).

Table 4
Breakdown of Percentages of Response Types for Similar and Dissimilar Migration and Control Contexts in Experiment 2

	Similar context		Dissimilar context	
Response type	Migration	Control	Migration	Control
Correct	55.8	59.6	61.5	61.7
LM/pseudo-LM	4.3	1.3	2.5	3.3
WM	14.0	13.8	9.3	9.2
Other	26.0	25.3	26.8	25.9

Note. LM = letter migration; WM = word migration.

LMs. The LM data replicated the surround-similarity effect observed previously. When the context was similar to the target, true LMs made up 3.0% of responses (7.1% of error responses), as measured by the difference in the frequency of LMs and pseudo-LMs observed in the migration and control conditions, respectively; this difference was significant, $F_1(1, 19) = 25.02$, $p < .001$; $F_2(1, 58) = 14.75$, $p < .001$. By contrast, when the context was dissimilar to the target, there were no true LMs: The number of LM responses was numerically less than the number of pseudo-LM responses, although the difference did not approach statistical significance, $F_1(1, 19) = 1.15$, $p > .20$; $F_2(1, 58) < 1$. This finding supports the lexical (or word conflation) account of LMs. According to this account, perception of the illusory word STOP when an observer is presented with the target–context pair *STEP* SOAP reflects the fact that both STEP and SOAP partially activate the representation of the word STOP. By contrast, an orthographically dissimilar context word like LOCK does not activate this representation, and so it is unlikely that the illusory word STOP will be perceived in this case.

As can be seen in Table 5, the similar contexts replicated the critical finding of the first experiment: True LMs occurred equally often in the same-position and adjacent-position conditions (the frequency was 3.0% in both cases). For the dissimilar contexts, the rate of pseudo-LMs exceeded the rate of LM responses for both the same-position and adjacent-position conditions, and the resulting negative estimates of true LMs did not differ for these two conditions, $F_1(1, 19) < 1$; $F_2(1, 58) < 1$. This result indicates that trials like *STEP* SHOP and *STEP* SOAP are equally likely to trigger perception of the illusory word STOP; put another way, the results suggest that SHOP and SOAP are approximately equally similar to the word STOP. In one sense, this may not seem surprising, given that SHOP and SOAP both share three out of four letters with the word STOP. However, both contexts are more likely to produce LM responses than the control context SNAP, which has the same outer letters. Thus, the interior letter *O* in the contexts SHOP and SOAP significantly increases the likelihood that the illusory word STOP will be perceived, but it is not critical that this letter has the same serial position in the context and illusory words. This aspect of the data is clearly at odds with position-specific coding schemes.

WMs. As in Experiment 1, participants in this experiment often reported the context word instead of the target word (e.g., *STEP* LOCK → “lock”). There was an effect of surround similarity on the frequency of these WMs: Participants made an average of 13.9% WM responses when the context was similar to the target, compared with 9.3% when the context was dissimilar to the target. The difference was significant, $F_1(1, 19) = 5.21$, $p < .05$; $F_2(1, 59) = 26.59$, $p < .001$. This finding is consistent with the idea that location uncertainty is related to a difficulty with perceptual individuation (e.g., Treisman & Schmidt, 1982). That is, it may be more difficult to bind the identity of a stimulus with its correct location when that stimulus is perceptually similar to other stimuli in the visual field.

The presence of WMs in dissimilar contexts may help to reconcile the apparent empirical contradiction discussed earlier. Un-

Table 5

Frequencies (in Percentages) of Letter Migrations (LMs), Pseudo-LMs, and True LMs (Difference) as a Function of Context/Position Condition in Experiment 2

Context/position condition	LM	Pseudo-LM	Difference
Similar			
Same	3.8	0.8	3.0
Adjacent	4.7	1.7	3.0
Dissimilar			
Same	2.7	3.5	−0.8
Adjacent	2.3	3.0	−0.7

like the present experiment and those reported by Mozer (1983), in which true LMs were observed only for similar word contexts, McClelland and Mozer (1986, Experiments 1 and 2) observed true LMs for both similar- and dissimilar-word contexts. One difference between the experiments was that we, like Mozer, required participants to report the identity of a probed word, whereas McClelland and Mozer's experiments required participants to report a single probed letter within the probed word. Consequently, there is no way of determining whether WMs occurred in the latter experiments. If a WM did occur, this would result in a response that would be classified as an LM (e.g., a participant who misperceived the location of the two words LAMP and HINT would report the letter *I* if prompted for the second letter of the left-hand word). It is therefore possible that the LMs that McClelland and Mozer observed for dissimilar contexts were the result of WMs.[3] This leads us to concur with Mozer's conclusion that true LMs occur only when the target and context are similar.

Other errors. The similarity of target and context did not affect the frequency of other error responses, which made up 25.7% of responses in the similar-context conditions and 26.4% of responses in the dissimilar-context conditions, $F_1(1, 19) < 1$; $F_2(1, 59) < 1$.

In summary, Experiment 2 replicated the main finding of Experiment 1 (i.e., that letters can migrate to adjacent positions in other words). As in the first experiment, these adjacent-position LMs occurred just as often as same-position LMs. In addition, the effect of surround similarity on LMs (McClelland & Mozer, 1986; Mozer, 1983; Shallice & McGill, 1978) was replicated, which is consistent with a lexical account of LM phenomena. Finally, the surround-similarity effect was extended to include WMs. Although WMs were observed for dissimilar contexts (unlike LMs), they occurred more often when the context was similar. This similarity effect may reflect failures to bind identity and location information, brought on by difficulties with perceptual individuation (e.g., Treisman & Schmidt, 1982).

Experiment 3

The results of the first two experiments showed no significant difference between the frequency of same-position LMs and different-position LMs. These data do not allow us to rule out a model in which the early coding of letter position is insensitive to the relative position of medial letters. For example, suppose that the stimulus *STOP* is coded as S_i, T_m, O_m, P_f, where the subscripts *i*, *m*, and *f* refer to initial, medial, and final letters, respectively. In this scheme the letter O would be coded as O_m in the words STOP, SHOP, and SOAP. It follows that adjacent-position LMs should occur just as often as same-position LMs for the stimuli in our first two experiments. In itself, this scheme does not explain how TL word pairs like CALM and CLAM can be distinguished, but it is possible to speculate that more detailed information regarding relative letter position becomes available later in processing (but is less likely to be available given the brief masked display conditions of the present experiments).

However, an alternative (and, we believe, more likely) possibility is that differences of one serial position are simply too subtle to detect with the present methodology. In Experiment 3, we therefore set out to test whether LMs could cross two letter positions (e.g., from Position 2 of the context to Position 4 of the target). It is possible to design four-letter word pairs which allow for the possibility of LMs that cross two positions (e.g., *PINE* HIDE → "dine"). However, this does not provide a fair comparison with our previous experiments, because LMs may be less likely to occur for exterior letters, which tend to be better perceived than medial letters (e.g., Estes, Allmeyer, & Reder, 1976).[4] Instead, we used five-letter words in Experiment 3, which allowed us to compare the frequency of same-position LMs, adjacent-position LMs, and two-letter distant LMs for medial letters. Observing LMs that cross more than one position would constitute even stronger evidence against position-specific coding than that obtained from our first two experiments. The relative frequency of LMs across these three conditions is also of theoretical interest. If, as in the above-described hypothesis, the relative position of medial letters is not coded, the number of LMs should be equivalent across the three conditions. However, if letter position is coded in a way that is flexible (and somewhat approximate) yet is sensitive to relative position, we should expect to observe a linear decrease in the number of LMs as migration distance increases.

Method

Participants. Twenty-nine undergraduates from the University of Bristol participated in the experiment in return for course credit. All were native speakers of English.

Stimuli and design. All of the stimuli in this experiment were five-letter words. Stimuli were constructed by developing triplets of closely matched items: a target word, a migration context, and a control context. Each member of a triplet had the same exterior letters and shared one interior letter. Migration contexts included a single interior letter that could replace an interior letter of the target to form another legal word (e.g., *PEACE* PLATE, which allows the migration response "place"). The control contexts were selected so that their interior letters could not replace an interior letter of the target to form a legal word (e.g., *PEACE* PHASE).

The potential migratory letter appeared in either Position 2 or Position 4 of the context word. The number of serial positions that this letter needed to cross to form an illusory word was varied over three levels: zero (i.e., same-position migrations, e.g., *PEACE* PLATE → "place"), one (i.e., adjacent-position migrations, e.g., *BENCH* BATCH → "beach"), or two

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[3] This may also explain the presence of true LMs for letters in digits in McClelland and Mozer's (1986) experiments, a result that is otherwise incompatible with the lexical account of LMs.

[4] Data from another experiment we have conducted indicate that the LM rate interacts with serial position and target position, and that cross-position LMs to initial letter positions are rare.

(e.g., *ABIDE* ARISE → "aside"). Factorial manipulation of these three factors—context type (migration or control) × letter position (2 or 4) × migration distance (0, 1, or 2 positions)—resulted in 12 stimulus conditions. There were 15 targets in each condition, resulting in a total of 180 target–context pairs. Different targets were used in each migration condition, and none of the potential illusory words occurred as stimuli. Participants saw each of the targets twice: once with the migration context and once with the control context. Two versions of the experiment were run so that target position was counterbalanced across versions (e.g., half of the participants saw the trial *PEACE* PHASE, and half saw the trial PHASE *PEACE*). Examples of the stimuli can be seen in Table 1.

Procedure. This experiment followed an identical procedure to that of Experiment 2. Participants with mean accuracy rates of less than 30.0% were dropped from the analyses; this resulted in the exclusion of 8 participants. Also, 1 participant whose mean accuracy was very high (82.0%) was excluded.[5] This left 20 participants: 10 for each of the two versions of the experiment.

Results and Discussion

The overall accuracy rate was 46.6%; presumably, the lower accuracy in this experiment reflects the greater difficulty imposed by the additional letters in the display (i.e., 10 letters in all vs. 8 letters in the previous experiment with the same display duration). Once again, accuracy of report was greater for targets presented on the right ($M = 53.1\%$) than for targets presented on the left ($M = 40.1\%$), $F_1(1, 19) = 4.19$, $p < .06$; $F_2(1, 179) = 80.98$, $p < .001$.

As in the previous experiments, responses were categorized as either correct, LMs, pseudo-LMs, WMs, pseudo-WMs or other errors. Table 6 shows the percentages of responses falling into each of these five response categories, broken down by context condition. As in the other experiments, most errors were WM responses or other errors. Here, though, we focus on the LM errors.

Overall, there were 185 LM responses and 77 pseudo-LM responses. The frequency of LM and pseudo-LM responses did not vary as a function of target position, $F_1(1, 19) < 1$; $F_2(1, 89) < 1$. Table 7 shows the percentages of LM and pseudo-LM responses in the three migration-distance conditions. The number of LMs significantly exceeded the number of pseudo-LMs in the same-position, $F_1(1, 19) = 30.14$, $p < .001$; $F_2(1, 29) = 18.43$, $p < .001$, adjacent-position, $F_1(1, 19) = 13.47$, $p < .01$; $F_2(1, 29) = 13.59$, $p < .01$, and distant-position, $F_1(1,19) = 9.11$, $p < .01$; $F_2(1, 29) = 5.12$, $p < .05$, conditions.

We also conducted analyses to test for differences in the rate of true LMs across the three position conditions. These confirmed the significant linear trend in the data, indicating a monotonic decrease in the frequency of LMs as migration distance increased, $F_1(1, 19) = 11.01$, $p < .01$; $F_2(1, 87) = 12.58$, $p < .01$. A pairwise comparison of the same-position and adjacent-position conditions revealed no significant difference in the rate of LMs, $F_1(1, 19) = 1.53$, $p > .05$; $F_2(1, 87) = 1.21$, $p > .05$. The difference between the adjacent-position and distant-position conditions was also nonsignificant, $F_1(1, 19) = 2.33$, $p > .05$; $F_2(1, 87) = 1.71$, $p > .05$.

Table 6
Breakdown of Percentages of Response Types for Migration and Control Contexts in Experiment 3

Response type	Context Migration	 Control
Correct	45.3	47.8
LM/pseudo-LM	10.3	4.3
WM	17.7	20.5
Pseudo-WM	1.0	1.3
Other	25.7	26.1

Note. LM = letter migration; WM = word migration.

Table 7
Percentages of Letter Migrations (LMs) as a Function of Migration Distance in Experiment 3

Migration distance	LM	Pseudo-LM	Difference	p[a]
0 (same position)	15.3	6.5	8.8	.000
1 (adjacent position)	11.0	4.8	6.2	.001
2 (distant position)	4.5	1.5	3.0	.004

[a] Significance level of test (over participants) comparing frequency of LMs and pseudo-LMs.

As in the previous two experiments, LMs were observed not only between corresponding positions but also between adjacent serial positions. Even more impressive, the results showed that letters can migrate across two serial positions. This constitutes clear evidence against position-specific coding schemes and favors a more flexible method of coding letter position. These data also replicate our previous experiments in showing no significant difference between the LM rates for the same- and adjacent-position conditions (although, as in Experiment 1, there was a numerical difference indicating more LMs for the same-position condition). In itself, this aspect of the results could be accommodated by a coding scheme in which the relative position of medial letters is unavailable early in the processing of a letter string. However, this scheme incorrectly predicts that the LM rate should be just as high for the two-letter distant condition as it is for the same-position condition. The evidence of a linear decrease in LMs as migration distance increases supports a model in which letter position is coded in a way that is flexible, and somewhat approximate, but which retains sensitivity to the relative position of medial letters.

General Discussion

The main goal of this study was to test a strong prediction made by position-specific coding: that letters will only migrate between corresponding letter positions, not between noncorresponding letter positions. Previous studies of LM phenomena have observed a strong tendency for position preservation (e.g., Shallice & Warrington, 1977), and this has been interpreted as support for position-specific coding (e.g., Ellis et al. 1987; Hinton & Shallice, 1991; Mozer, 1983). The findings reported here, however, suggest that this position-preservation effect is an artifact of lexical and graphotactic constraints. When these constraints are removed, a significant number of noncorresponding LMs are observed. This outcome contradicts the prediction made by position-specific coding schemes. Given the important role that letter coding schemes play in the functioning of models, these findings pose a challenge

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[5] The exclusion of these participants had no effect on the pattern of results in this experiment, or the outcomes of the statistical analyses.

to most current theories of visual word recognition (e.g., Coltheart, et al., 2001; Grainger & Jacobs, 1996; Harm & Seidenberg, 1999; Hinton & Shallice, 1991; McClelland & Rumelhart, 1981; Plaut, 1999; Plaut et al., 1996; Zorzi et al., 1998). The results favor an alternative type of letter coding scheme, as outlined below.

What Is the Locus of LM Phenomena?

The correct interpretation of LM phenomena depends on determination of the locus of these effects. One theoretical possibility is that the tendency to report illusory words does literally involve the migration of letters from one part of the visual field to another (Treisman & Souther, 1986). According to this feature-integration account, when attention is overloaded, letters are sometimes identified but not localized, allowing letters to be recombined incorrectly to form illusory words. At least two distinct versions of this account are possible. In one version, information about each letter's serial position is available, but not information about spatial location (e.g., the system detects that an *O* occurred in the second position but does not determine which visual field it occurred in). However, this does not explain the occurrence of cross-position migrations in our data.

A second version of the feature-integration account posits that attentional overloading interferes with the acquisition of information about either within-word or between-word location. This version does explain the occurrence of cross-position LMs but cannot explain the surround-similarity effect, whereby LMs occur for similar target–context pairs (e.g., *STEP* SHOP) but not for dissimilar target–context pairs (e.g., *STEP* FROG; McClelland & Mozer, 1986; Mozer, 1983; Shallice & McGill, 1978). Experiment 2 replicated this effect for both same-position and adjacent-position LMs. This argues against either of these types of migration reflecting prelexical processes. If letters were subject to a relatively early perceptual drift, then LM errors should be expected to occur for dissimilar contexts. The complete absence of LM responses for dissimilar contexts in Experiment 2 points to a later, lexical locus. According to a lexical (word conflation) account, LMs occur for similar target–context pairs like *STEP* SOAP because both words partially activate the representation of the LM response (in this case, "stop"). By contrast, LMs do not occur for dissimilar target–context pairs, because the orthographically dissimilar context word does not activate the lexical representation of the illusory word (e.g., FROG does not activate the representation of STOP).

Before proceeding, it is worthwhile to consider a form of lexical account different from the one that is being proposed here. We have argued for a lexical account in which the illusory word is activated above threshold, resulting in the perceptual experience of this word. An alternative possibility, however, is that participants use a postperceptual strategy to guess the word that is most consistent with the limited perceptual input available. This issue is difficult to avoid in tasks like perceptual identification, in which the input stimulus is presented either very briefly or in a visually degraded fashion, and there is an old debate about whether performance in this task reflects primarily perceptual processes or postperceptual (e.g., sophisticated guessing) strategies (e.g., Goldiamond & Hawkins, 1958; Neisser, 1967). Paap, Johansen, Chun, and Vonnahme (2000) have recently sought to reopen this debate, arguing that the effects of word frequency in the Reicher–Wheeler task are the result of postperceptual decision processes rather than any genuine effect of word frequency on the perception of words (cf. Grainger & Jacobs, 1994). This is an important theoretical debate, and we agree that postperceptual guessing strategies can influence performance on perceptual identification tasks (indeed, our account of the factors that may have contributed to a misinterpretation of position-preservation phenomena in previous LM studies is consistent with the notion of response biases). Nevertheless, it is important to emphasize that the possibility of postperceptual lexical influences on participants' responses does not detract from our conclusions concerning letter position coding. It is conceivable that participants in our task are subject to a response bias that influences them to report, for example, the word "stop" when the target is actually the lower frequency word *STEP*. However, there is no a priori reason why this bias should be any stronger when the context word is SHOP (or SOAP) than it is with a control context like SNAP. Rather, the observed differences between these contexts must reflect differences in the perceptual input. Whether this perceptual input is acted upon by a normal perceptual process of lexical activation (as we contend) or a postperceptual lexical guessing strategy, the critical issue is that the input itself allows migration errors, even when the potential migratory letter occupies different positions in the context word and the illusory word. Consequently, we do not make any further distinction between these two lexical accounts in the following discussion.

Implications of Cross-Position LMs for Position-Specific Coding

The lexical account of LM errors as instances of word conflation suggests that this phenomenon can be exploited as a tool for measuring the relative perceptual similarity of letter strings. In Experiments 1 and 2, the target was always a neighbor of the migration response, whereas the perceptual similarity of the context word and the migration word was varied. In the (similar-context) same-position condition, the context was an orthographic neighbor of the migration word (e.g., given the display *STEP* SHOP, SHOP is a neighbor of the migration response "stop"). In the (similar-context) adjacent-position condition, the context was not an orthographic neighbor of the migration word in the conventional sense, although it shared three out of four letters with the migration word. For example, the context SOAP is not a neighbor of the migration word SHOP, according to the conventional definition, because one of the three letters that it shares with STOP (the *O*) occurs in a different position in the two words; we refer to pairs like this as *neighbors once-removed* (N1R). Finally, in the (similar-context) control condition, the context shared two out of four letters with the migration word (e.g., *STEP* SNAP). Once again, there is no conventional name for this form of similarity; to facilitate the present discussion, we refer to pairs like SNAP and STOP as *double-substitution neighbors* (DSNs). The number of migrations associated with these three different types of contexts provides an index of their relative perceptual similarity. The fact that the same-position condition resulted in more illusory word reports than the control condition implies that neighbors (*N pairs*) are more similar than DSN pairs (e.g., STOP and SHOP are more similar than STOP and SNAP). This result is not especially surprising, especially given evidence of the effects of neighbor similarity in a variety of tasks and paradigms (e.g., Andrews, 1997; Coltheart, Davelaar, Jonasson, & Besner, 1977; Forster & Hector, 2002; Grainger, 1990; Paap et al., 2000). A more theoretically interesting result is the finding that the adjacent-position condition resulted in more illusory word reports than the control condition. This implies that N1R pairs are more similar than DSN pairs (e.g., STOP and SOAP are more similar than STOP and SNAP). This result is problematic for position-specific coding models, which predict equivalent similarity of N1R pairs and DSN pairs; for example, SOAP and SNAP both share two position-specific units with STOP.

The third comparison offered by the manipulation of context in the first two experiments is between N pairs and N1R pairs. Although the present experiments failed to find a statistically significant difference between the same- and adjacent-position conditions (e.g., between the contexts SHOP and SOAP), it would be premature to conclude that N pairs and N1R pairs are of equivalent perceptual similarity. Experiment 1 obtained a numerical difference between the two conditions (and a comparable result was obtained in Experiment 3), and this difference may have been significant in a more powerful experiment. Nevertheless, the absence of any clear difference between the two conditions in the present experiments is also at odds with the predictions that follow from position-specific coding models.

None of the various different versions of slot-coding schemes that have been adopted in existing computational models are able to explain the patterns of perceptual similarity suggested by the current data. Our discussion so far has focused on the simplest variant, which is the four-slot scheme used in the original IA model. The DRC model uses a slightly more complex scheme than the original IA model, enabling it to code stimuli that vary in length (up to eight letters). Stimuli are left-aligned, so that the first letter is always assigned to Slot 1, the second letter to Slot 2, and so forth, and any units that do not contain letters are padded with space characters. Nevertheless, four-letter words are coded by Slots 1–4, and so the situation is exactly the same as in the simpler four-slot scheme. Right-aligned slot-coding schemes are also possible; for example, a four-letter word could be coded by activating units in Slots 5–8 rather than Slots 1–4. However, this clearly would not make any difference to the present argument. A justified alignment can also be used, in which the end letters are always in the outer slots (i.e., Slots 1–8), and other letters are positioned relative to these; for example, a four-letter word could be coded by activating units in Slots 1, 2, 7, and 8. A scheme of this sort was proposed by Jacobs, Rey, Ziegler, and Grainger (1998). Once again, though, when all of the relevant words (i.e., the target, context and migration word) are of the same length, the argument is exactly the same: In this case, N1R pairs like STOP and SOAP have corresponding letters in Slots 1 and 8, but different letters in Slots 2 and 7. The variant of slot coding used by Harm and Seidenberg (1999) also has eight slots. It differs from the DRC model's left-aligned scheme in that words are centered on their vowel (only monosyllabic words are coded by this scheme). The first vowel is always assigned to Slot 4, and other letters are arranged relative to this letter. For example, the word STOP would be coded by the units S_2, T_3, O_4, and P_5. Like the other forms of slot coding, vowelcentric coding is unable to explain adjacent-position migrations. In fact, it has even greater difficulty in explaining this phenomenon, as can be seen by considering the similarity between the codes for STOP and SOAP in this scheme. The word SOAP is coded by the units S_3, O_4, A_5, and P_6; this set shares only a single feature (O_4) with the corresponding set for STOP. It follows that this scheme should not predict a display like *STEP* SOAP to result in reports of the illusory word "stop"; the same problem applies for virtually all of the trials in the adjacent-position migration condition (e.g., *FIST* FLAT → "fast"; *CLIP* CAMP → "clap").

Can Position-Specific Coding Be Saved?

A possible modification to try to save position-specific coding would be the introduction of position uncertainty by coding each letter of the stimulus with activity across several letter units (i.e., *slots plus slop*).[6] For example, suppose that a letter *O* in the second position results in a gradient of activity over slots, so that the *O* node in the second position is most strongly activated, but the *O* nodes in the first and third positions are also somewhat activated, as is, to a lesser extent, the *O* node in the fourth slot. This blurring of position information will increase the degree of overlap between words like STOP and SOAP, because both words will activate the *O* nodes in Positions 2 and 3.

As an independent construct, the introduction of location uncertainty is well-motivated and can be justified on independent empirical grounds: For example, tasks in which participants are asked to report the letters in briefly presented, random letter strings reveal frequent location errors (e.g., Estes et al., 1976; Mewhort, Campbell, Marchetti, & Campbell, 1981). However, we do not believe that grafting this construct onto existing slot-coding schemes offers a satisfactory solution to the problems associated with position-specific coding.

The most important problem facing position-specific coding is the alignment problem, and this problem is in no way ameliorated by the introduction of location uncertainty. For example, a "sloppy" form of slot coding may explain why the word STOP is more likely to be confused with the word SOAP than it is with the word SNAP. But it does not explain how the word STOP could be recognized in a novel compound like FULLSTOP. The alignment problem arises whenever familiar patterns are presented in unfamiliar positions. Slot-coding schemes link the representations of familiar words to specific letter positions. However, the ability to recognize a familiar word is not dependent on the specific letter positions that it occupies. For example, suppose that the visual word recognition system has learned that the pattern $\{S_1, T_2, O_3, P_4\}$ at the letter level corresponds to the word STOP. Having learned this word, the system ought to be able to recognize it when it occurs in a different context—for example, in a word like FULLSTOP (or in an entirely novel compound like HALFSTOP). This is not possible when a slot-coding scheme is used, because the STOP component of FULLSTOP activates a different set of nodes from those activated by the familiar word STOP—the familiar unit is misaligned with the learned code. When simple slot coding is used, the STOP component of FULLSTOP is coded by Slots 5–8 (i.e., S_5, T_6, O_7, P_8), and hence there is no way for the recognition system to apprehend the similarity between FULLSTOP and STOP. It is surely implausible to suggest that there is so much

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[6] We thank Sally Andrews for suggesting this term.

position uncertainty in the representation that an *S* in the fifth position could prime a lexical representation in which *S* occurs in the first position. Thus, models that use slot-coding schemes (sloppy or otherwise) have difficulty explaining how familiar words can be recognized in novel contexts, especially in the common case of novel compounds (for related discussions, see Andrews & Davis, 1999; Bowers, 2002).

A deeper theoretical objection concerns the appropriateness of combining position uncertainty with position specificity. The current experiments provide further evidence that letters are not coded in a way that strictly preserves letter position: The early processing of a letter string does not appear to provide precise information about the specific position of individual letters (at least for medial letters). The fundamental question raised by the present data is how modelers should respond to evidence of nonspecific letter-position coding. A continued commitment to the existence of position-specific letter units seems (to us) to be a rather incongruous response. A theoretical solution that relies on a proliferation of such units to simulate position independence seems analogous to the early cosmologists' use of epicycles to preserve the notion of spherical orbits in the face of orbits that were clearly not spherical. A more appropriate response to the present findings seems to us to be to concede that letter position is coded in a relatively flexible way that does not involve position-specific letter units. Some alternatives are considered below.

It is also relevant to note that there are difficult implementational issues surrounding the introduction of such a scheme into existing slot-coding models like the original IA model and those models derived from it (e.g., the DRC and MROM models). A key assumption of these models is that the word-selection process depends on the existence of inhibitory bottom-up connections between letter nodes and incompatible word nodes. For example, the letter unit O_2 sends inhibitory connections to all word nodes representing words that do not contain an *O* in Position 2 (including, e.g., the STOP word detector). Consequently, the presence of activity in multiple *O* letter nodes that code different positions will result in strong inhibitory inputs to word nodes. These inhibitory connections play a particularly important role in the DRC model, which relies on bottom-up inhibition to prevent nonword and low frequency word stimuli from being captured by high frequency neighbors. For example, in the absence of bottom-up inhibition, presentation of a low frequency word like THUS may result in the dominant activation of the node that codes the word THIS. To avoid this lexical capture problem, Coltheart et al. (2001) used very high values of the letter–word inhibition parameter: .435 to simulate reading aloud and .300 to simulate lexical decision (these values can be compared with the corresponding value of .040 in McClelland & Rumelhart's, 1981, original IA model). Given such high settings of the bottom-up inhibition parameter, even weak activity in a single incompatible letter will prevent any word nodes from receiving positive net input from the letter level. Thus, adding location noise to the coding of SOAP will not help to explain how the STOP word detector is partially activated; instead, it will prevent even the SOAP word detector from becoming activated. For position uncertainty to be introduced, it would be necessary to eliminate (or at the very least severely reduce) bottom-up inhibitory connections between a letter node and word nodes that contain that letter in a different position. A greatly reduced reliance on the mechanism of bottom-up inhibition would in turn necessitate a much stronger reliance on lateral (word–word) inhibition, which would involve substantial changes to the DRC model. In itself, this does not represent an objection to sloppy slot-coding, but it does nicely illustrate how the choice of coding scheme has important implications for the way in which computational models of reading work (or do not work).

Alternatives to Position-Specific Letter Coding

The above considerations point to the need for a form of position coding that is considerably more flexible than slot coding. In particular, a letter's position needs to be coded relative to other letters in the string rather than in terms of its absolute position. This enables word representations to be primed by letter strings that contain the correct letters in the incorrect positions (which is essential for explaining the present results, as well as for solving the alignment problem). A number of alternatives to position-specific coding have been suggested: Wickelcoding, subsyllabic coding, open-bigram coding, and spatial coding. In the remainder of this article, we consider each of these coding schemes in turn, evaluating their capacity to explain the present data.

Wickelcoding. One alternative to position-specific coding is to code letter order in terms of local context. For example, the *A* in CAT can be coded by noting that it has a *C* to its left and a *T* to its right. The idea of using local context to avoid explicit coding of serial order was suggested by Wickelgren (1969). This contextual coding scheme, which is often referred to as *Wickelcoding*, has been adapted for use in a number of connectionist models of word processing (Mozer, 1983; Rumelhart & McClelland, 1986; Seidenberg & McClelland, 1989). *Wickelfeatures* are triples of individual features, and a set of these triples can be used to specify a word. For example, if the features are individual letters, then STOP would be coded as the set of Wickelfeatures {_ST, STO, TOP, OP_}, where _ indicates a word boundary. A completely general implementation of this scheme requires tens of thousands of Wickelfeatures.

Wickelcoding's handling of the alignment problem is a great improvement over position-specific coding. For example, if one has learned the set of Wickelfeatures that codes the word STOP, it should be possible to recognize this word in different contexts like FULLSTOP or STOPWATCH, given that three of its four Wickelfeatures are present in these contexts. Nevertheless, Wickelcoding suffers from several shortcomings. Satisfactory generalization is very difficult to achieve when Wickelcoding is used, because spelling–sound correspondences (e.g., the sound associated with the letter *P*) are dispersed over an extremely large number of local contexts (e.g., _PA, ELP, OP_, etc.; Plaut et al., 1996). This problem was noted by Besner et al. (1990) in their analysis of the Seidenberg and McClelland (1989) model's nonword naming performance. Other problems with Wickelcoding are discussed by Pinker and Prince (1988).

Wickelcoding is also unable to explain the critical aspects of the present data. For example, in this scheme, the word STEP shares no features with the word SHOP: STEP is coded by the set {_ST, STE, TEP, EP_}, whereas SHOP is coded by the set {_SH, SHO, HOP, OP_}. This means that Wickelcoding cannot explain the surround-similarity effect, because the target–context pair *STEP* SHOP is no more similar than the target–context pair *STEP* FROG. Indeed, this scheme fails to explain why LMs should occur for either same-position or adjacent-position cases. A possibility that deserves further consideration, however, is that the present data might be accommodated by the more flexible form of Wickelcoding used in Mozer's MORSEL (multiple object recognition and attentional selection) model, which incorporates the notion of positional uncertainty (Mozer, 1991; Mozer & Behrmann, 1990).

Plaut et al.'s subsyllabic coding. The Plaut et al. (1996) model of reading was developed in response to the problems of the preceding PDP model of Seidenberg and McClelland (1989). In particular, Plaut et al. (1996) introduced a new form of letter-position coding that was designed to solve the problems associated with Wickelcoding: "the dispersion problem prevented the [Seidenberg & McClelland, 1989] network from exploiting the structure of the English spelling-to-sound system as fully as human readers do. We set out, therefore, to design representations that minimize this dispersion" (p. 65). Their solution was a form of slot-coding that partitions syllables into the subsyllabic components of *onset*, *vowel*, and *coda*. For example, the word BLIND would be coded by activating the *B* and *L* onset units, the *I* vowel unit, and the *N* and *D* coda units. When multiple letters are activated in a single subsyllabic cluster, the relative order of these letters is determined by graphotactic constraints on the structure of English orthography. For example, there are no English words that begin with the letters *LB*, and so the coactivation of *B* and *L* in the onset must indicate an initial *BL* cluster. The model's knowledge of graphotactic constraints is encoded via a left-to-right ordering of graphemes within each cluster (e.g., within the onset cluster the grapheme *B* is listed before the grapheme *L*). In passing, we note that a rather implausible aspect of this coding scheme is that it is incapable of coding most nonwords veridically; for example, the nonword LBIDN would be coded in a way that makes it indistinguishable from the word BLIND. Indeed, Plaut et al.'s model would pronounce LBIDN as "blind." It is perhaps not surprising, then, that subsequent PDP models of reading have used position-specific letter units, in which letter order is coded unambiguously (e.g., Harm & Seidenberg, 1999).

In addition to its difficulties in coding letter order, the subsyllabic coding scheme is also unsuited to explaining the LM phenomena observed in the present experiments. To take just one example, consider the trial *SHADE* SKATE. Experiment 3 showed that displays of this sort result in a significant number of true LMs that cross two positions (e.g., the illusory word SHAKE is reported more often following *SHADE* SKATE than following *SHADE* STAGE). This implies that SHAKE and SKATE are more similar than SHAKE and STAGE. But Plaut et al.'s (1996) coding scheme cannot accommodate this pattern, because the *K* unit in the onset slot is unrelated to the *K* unit in the coda slot.

Open bigrams. A different form of local-context coding was proposed by Whitney (2001) in her SERIOL (sequential encoding regulated by inputs to oscillations within letter units) model. In this scheme, a letter is coded in terms of all of the ordered letter pairs that occur in the stimulus. For example, the word STEP would be coded by the set {ST, SE, SP, TE, TP, EP}. Schoonbaert and Grainger (2004), who propose a similar method of coding letter position, refer to this scheme as *open-bigram coding*. One of this scheme's advantages is that it encodes letter order in a way that is not dependent on absolute letter position. This enables open-bigram coding to avoid the alignment problem associated with position-specific letter coding schemes. For example, all of the bigrams in the word STOP are also contained in the set of bigrams for the letter string FULLSTOP.

Open-bigram coding is also successful in explaining the key aspects of the present data. First, this scheme is compatible with a lexical account of LMs: The (similar) migration contexts used in these experiments are more similar to the illusory words than are the control contexts. For example, the migration context SHOP shares three features with the word STOP (the open bigrams *SO*, *SP*, and *OP*), whereas the control context SNAP shares only a single feature (the open bigram *SP*). This correctly predicts that the illusory word "stop" will be reported more often for the display *STEP* SHOP than for the display *STEP* SNAP. When the target and context words share only a single letter (as in the case of dissimilar pairs like *STEP* FROG), they will not share any bigrams, and thus open-bigram coding correctly predicts the surround-similarity effect and the complete absence of LMs for dissimilar contexts.

An interesting prediction made by open-bigram coding is that adjacent-position LMs should occur just as often as same-position LMs. The reason for this is that, in this scheme, N1R pairs like STOP and SOAP are just as similar as orthographic neighbors like STOP and SHOP; in both of these examples, the three open bigrams *SO*, *SP*, and *OP* are shared. This reflects the fact that open-bigram coding is insensitive to the distance between letter pairs (e.g., the *SO* unit responds equally to SOAP and SHOP). Thus, the prediction is that the illusory word STOP will be reported equally often for the displays *STEP* SHOP and *STEP* SOAP. This is consistent with the results of Experiments 1 and 2. In Experiment 3, there was a linear relationship between migration distance and LM rate, although the difference between the same- and adjacent-position conditions did not attain significance, and so this finding is not inconsistent with the open-bigram scheme. This account correctly predicts fewer LMs for the condition in which the migrating letter must cross two serial positions, because this necessitates the reversal of a medial bigram (e.g., the relative position of the *S* and *I* letters is reversed in ASIDE and ARISE). Further experiments are under way to test the critical prediction made by open-bigram coding (i.e., that adjacent-position LMs occur just as often as same-position LMs). As far as the present experiments are concerned, though, open-bigram coding appears to provide a good account of the data.

Spatial coding. Another alternative to position-specific letter coding is used in the SOLAR (self-organizing lexical acquisition and recognition) model (Davis, 1999, 2004). This scheme assumes an orthographic input layer comprising position-independent letter units. Activity at this orthographic input level codes information about relative (rather than absolute) letter position. In one version of this scheme, called *spatial orthographic coding*, the relative order of the letters in a string is coded by the relative activity of the letter nodes (Davis, 1999).[7] This approach has its origins in Grossberg's (1978) use of spatial patterns to encode temporal input sequences; more recently, similar coding schemes have been used

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[7] The current version of the SOLAR model (Davis, 2001 uses a related type of sequence coding scheme called *phase coding*, which enables the coding of uncertainty regarding both letter identity and letter position. The details of this scheme are beyond the scope of this article, but its implications for the perceptual similarity of letter strings are essentially the same as those that follow from the spatial coding scheme described here.

by Page (1994) in a model of melody perception and by Page and Norris (1998) in their primacy model of serial recall. When this type of coding is used, each possible letter string is coded by a unique spatial-activity pattern. However, letter strings that have common letters are coded by relatively similar spatial codes, even if the common letters are found in different serial positions. In the SOLAR model, each word detector computes its input by calculating the match between two spatial codes: (a) the spatial code corresponding to the word represented by this detector and (b) the spatial orthographic code corresponding to the input stimulus. A match score is calculated by evaluating the degree of pattern overlap between these two spatial codes. Formulas for this calculation are detailed in Appendix B. It should be noted that the calculation does not rely on a standard dot product—that is, it is not the case that later letters (which are coded by smaller values) play a less important role in the match calculation.[8] Furthermore, a letter that is common to the two codes contributes to the match score even if it occurs in different serial positions in the input stimulus and the word coded by the word detector.

Some examples of spatial coding are shown in Figure 1. As can be seen, the codes for STOP and SHOP are quite similar: There is perfect overlap in the codes for the letters *S*, *O*, and *P* (this results in a match score of .75). The codes for STOP and SOAP are also quite similar: Again, there is overlap in the codes for the letters *S*, *O*, and *P*, although the overlap is not perfect this time because the magnitude of activity in the *O* unit differs slightly in the two codes (in this case, the match score is .69). However, the codes for STOP and SLAP are less similar, because they overlap for only two letters (the match score is .50). Thus, the spatial codes for N1R pairs like STOP and SOAP are more similar than the codes for DSN pairs like STOP and SLAP, but they are less similar than the codes for N pairs like STOP and SHOP, which is consistent with the lexical account of the results of the first two experiments.

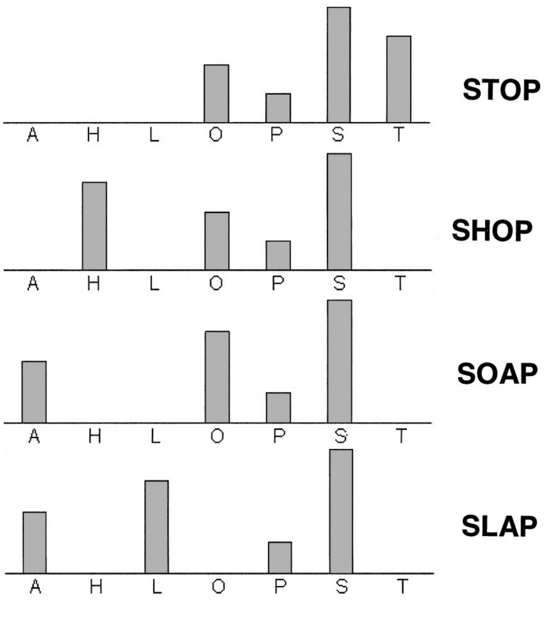

Figure 1. Examples of spatial coding for the words STOP, SHOP, SOAP, and SLAP.

The relative pattern of similarities among letter strings that share three out of five letters is also consistent with that suggested by the results of Experiment 3. For example, for SWORE and STORE, in which all common letters are in identical positions, the match score is .80; for BEACH and BATCH, in which one common letter is displaced by one position, the match score is .74; and for ASIDE and ARISE, in which one common letter is displaced by two positions, the match score is .65. All three of these cases are more similar than ASIDE and ALIKE, which share only three letters, resulting in a match score of .60.

Other Issues

Although our principal interest in the present experiments was LM errors, there are a couple of other aspects of the data that are worth commenting on. The first of these concerns other errors, which were the most common form of errors. Post hoc inspection of these errors showed that a large proportion involved possible migrations of letters from the context word to the target, such as *BLED* BAND → "blend." The percentage of other errors that contained interior letters from the context was 41% in Experiment 1, 46% in Experiment 2, and 51% in Experiment 3 (in the latter case, only two of the three interior letters were counted so as not to include the interior letter that was common to the target and context words). This suggests that letters migrated between words in the display more often than is suggested by the relatively low LM rate. It is not especially surprising that the illusory words resulting from LMs are sometimes words other than the designated LM response. As with the designated LM responses, though, some caution is necessary in interpreting nondesignated LM responses. It is more difficult to determine a suitable baseline for measuring the number of true LMs in this case, because the migration and control contexts often shared internal letters. Nevertheless, analyses that take this into account suggest that the true rate of undesignated LMs is relatively high. For example, in a subset of the other errors from Experiment 3 in which the migration and control contexts shared only a single interior letter (enabling a satisfactory baseline), 51% of the erroneous responses contained one of the unique letters from the displayed context, compared with 26% that contained a unique letter from the matched context that was not in the display. We can therefore estimate that around 25% of other errors in this experiment involved LMs that produced an illusory word other than the designated LM response.

Undesignated LMs provide a potentially interesting source of data. However, the central question of interest in this article—the extent to which LMs preserve letter position—cannot be properly assessed by examining these errors. Although they often involve positional displacement of letters in the target and/or the context, the likelihood of undesignated LMs is undoubtedly subject to the same orthotactic and lexical constraints that motivated our initial critique of the interpretation of position preservation in LMs. For this reason, we have not attempted to exploit undesignated LM errors to test hypotheses concerning letter-position coding.

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[8] The match scores for any pair of letter strings can be found by using the MatchCalculator program, available on the Web at www.maccs.mq.edu.au/~colin/matchCalc.zip. The match scores listed in the text are produced by setting $sigma_r = 3$, $w_I = 1$ (the latter is the simplest choice, which assumes that each letter position contributes equally to the calculation).

WMs

The other interesting issue raised by the present data concerns the WM phenomenon. Although WM responses occurred relatively often in our experiments (making up 26% of error responses in Experiment 1, 30% in Experiment 2, and 36% in Experiment 3), this phenomenon has only been reported in one other study of LMs (Mozer, 1983). It is not surprising that studies in which participants were asked to report all of the words in the display (e.g., Allport, 1977; Shallice & McGill, 1978) or just a single letter (e.g., McClelland & Mozer, 1986) have failed to detect WMs. However, it seems surprising that only one of the experiments that have used a cued partial-report methodology noted this phenomenon. It is likely that some proportion of the WM responses in our data reflect trials on which the participant simply reported the one word that they did see, even though it was in the noncued position. Nevertheless, on the basis of the self-reports of various participants during debriefing, as well as our own experience of the phenomenon, we are confident that genuine confusions concerning the position of the two words do occur. In another experiment that we recently conducted, participants who made WM responses were immediately asked the identity of the other word in the display. On approximately half of these trials, participants responded with the target word, suggesting that they had correctly identified both words but had incorrectly localized either the probe or (more likely) the words. Further investigation of this phenomenon may provide insights into preattentive processing and debates about serial versus parallel processing of word stimuli (e.g., Kahneman & Chajczyk, 1983; van der Heijden, Hagenaar, & Bloem, 1984) as well as the mechanisms underlying the binding of information about location and identity.

In summary, the present data provide further evidence against position-specific coding schemes, but they are potentially compatible with letter coding schemes in which relative, rather than absolute, position is the critical variable. In particular, both open bigram coding schemes (Schoonbaert & Grainger, 2004; Whitney, 2001) and sequence-coding schemes like spatial coding (Davis, 1999, 2004) can capture the pattern of interword perceptual similarity implied by the present data. These schemes adopt different approaches to encoding the relative order of letters. In open-bigram coding schemes, relative letter order is coded by the activation of ordered letter pairs; for example, the presence of an *O* preceding a *P* results in the activation of an *OP* unit, irrespective of the number of letters separating these two letters. Spatial coding, however, is sensitive to both relative order and letter separation. Unlike open-bigram coding, then, this scheme predicts that LMs that maintain position should occur more frequently than adjacent-position LMs. There was some evidence for a trend in this direction in Experiments 1 and 3, although these experiments may not have been sufficiently powerful to detect a small difference. Further research exploring this and other differential predictions of the two schemes should help to elucidate the manner in which letter position is coded by the visual word recognition system.

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Appendix A

Stimuli Used in Experiments 1–3

Target word	Migration context	Control context	Migration word
Experiment 1 (same position): Position 2 → Position 2			
MUTE	MADE	MERE	MATE
HIVE	HAZE	HOLE	HAVE
TILE	TAKE	TUBE	TALE
DART	DIET	DENT	DIRT
SKIP	SHOP	SOUP	SHIP
DAME	DOLE	DUKE	DOME
LEND	LAID	LORD	LAND
HINT	HURT	HEAT	HUNT
CURE	CASE	CLUE	CARE
WIRE	WOKE	WAKE	WORE
COPE	CAGE	CUBE	CAPE
PICK	PARK	PORK	PACK
RULE	ROSE	RARE	ROLE
ROCK	RANK	RISK	RACK
DEAL	DULL	DOLL	DUAL
Experiment 1 (same position): Position 3 → Position 3			
RAGE	RICE	ROBE	RACE
FOAM	FIRM	FILM	FORM
BARK	BUNK	BULK	BANK
WEPT	WANT	WHAT	WENT
MICE	MALE	MODE	MILE
PINE	POPE	POSE	PIPE
CAFE	CONE	CUTE	CANE
WAGE	WIDE	WIFE	WADE
BAKE	BORE	BLUE	BARE
HIDE	HARE	HUGE	HIRE
PACE	PILE	POKE	PALE
LAKE	LONE	LOSE	LANE
SAFE	SOLE	SIDE	SALE
DESK	DOCK	DARK	DECK
SEND	SHED	SKID	SEED
Experiment 1 (adjacent position): Position 2 → Position 3			
GLUE	GENE	GATE	GLEE
SECT	SALT	SUIT	SEAT
CLIP	CAMP	CROP	CLAP
PRIM	PALM	POEM	PRAM
SPAN	SIGN	SOON	SPIN
BOOT	BAIT	BENT	BOAT
BELT	BAIT	BUTT	BEAT
GODS	GETS	GUYS	GOES
BOWL	BILL	BELL	BOIL
FOOL	FUEL	FEEL	FOUL
LOUD	LAID	LIED	LOAD
COOL	CALL	CELL	COAL
TREE	TUNE	TAME	TRUE
STEP	SOUP	SLAP	STOP
FINE	FLEE	FAKE	FILE
Experiment 1 (adjacent position): Position 3 → Position 2			
BLED	BIRD	BAND	BRED
MEND	MAID	MOOD	MIND
PEST	PLOT	PUTT	POST
BUCK	BEAK	BOOK	BACK
SNAP	SHOP	STEP	SOAP
SUNK	SOAK	SEEK	SANK
LIMP	LEAP	LOOP	LAMP
Experiment 1 (adjacent position): Position 3 → Position 2 (*continued*)			
FIST	FLAT	FORT	FAST
AGES	ALPS	AIMS	APES
SOIL	SEAL	SELL	SAIL
FEED	FOLD	FORD	FLED
THIN	TOWN	TURN	TWIN
LOSS	LIES	LIPS	LESS
SHOT	SALT	SEAT	SLOT
WARM	WHOM	WHIM	WORM
Experiment 2 (same position): Position 2 → Position 2			
MUTE	BACK	SEEK	MATE
HIVE	BANG	BOAT	HAVE
TILE	HAND	DUSK	TALE
DART	SICK	YELL	DIRT
SKIP	CHEW	FOLK	SHIP
DAME	VOID	BUSH	DOME
LEND	CAMP	HOPE	LAND
HINT	BUSY	FEAR	HUNT
CURE	HALF	GLOW	CARE
WIRE	LOAD	JAIL	WORE
COPE	VAIN	BUZZ	CAPE
PICK	FARM	BOLT	PACK
RULE	BORN	PAIR	ROLE
ROCK	GANG	FIRM	RACK
DEAL	JUMP	CORE	DUAL
Experiment 2 (same position): Position 3 → Position 3			
RAGE	LOCK	DEBT	RACE
FOAM	HURT	WILD	FORM
BARK	SUNG	GOLF	BANK
WEPT	FIND	THAN	WENT
MICE	GOLD	BEDS	MILE
PINE	COPY	ROSY	PIPE
CAFE	MINK	MOTH	CANE
WAGE	BODY	LEFT	WADE
BAKE	PORT	HOUR	BARE
HIDE	PORK	LEGS	HIRE
PACE	SILK	INKY	PALE
LAKE	PONY	POST	LANE
SAFE	DOLL	BODY	SALE
DESK	LACE	CARE	DECK
SEND	CREW	CHIC	SEED
Experiment 2 (adjacent position): Position 2 → Position 3			
GLUE	JERK	PATH	GLEE
SECT	WAVE	DUTY	SEAT
CLIP	TASK	DRUG	CLAP
PRIM	NAVY	SORE	PRAM
SPAN	MILK	BOOK	SPIN
BOOT	DAMP	MERE	BOAT
BELT	RAGE	DUMP	BEAT
GODS	TEAM	FURY	GOES
BOWL	MINE	RENT	BOIL
FOOL	BUSH	HELP	FOUL
LOUD	PAGE	BIKE	LOAD
COOL	NAME	BENT	COAL
TREE	GULF	GASP	TRUE
STEP	LOCK	CLAN	STOP
FINE	BLUR	JAZZ	FILE

(*Appendixes continue*)

Appendix A (*continued*)

Target word	Migration context	Control context	Migration word
Experiment 2 (adjacent position): Position 3 → Position 2			
BLED	PURE	WING	BRED
MEND	QUIT	COOK	MIND
PEST	CROP	KITE	POST
BUCK	OVAL	WHOM	BACK
SNAP	GROW	GREW	SOAP
SUNK	WRAP	AGED	SANK
LIMP	GOAT	FROG	LAMP
FIST	DEAR	TORN	FAST
AGES	DOPE	LAMP	APES
SOIL	GRAB	RULE	SAIL
FEED	ISLE	CORN	FLED
THIN	BOWL	WORD	TWIN
LOSS	GREY	COPY	LESS
SHOT	BELL	BEAR	SLOT
WARM	SHOW	EPIC	WORM
Experiment 3 (same position): Position 2 → Position 2			
AFTER	ALTAR	ACTOR	ALTER
BILLY	BULKY	BALMY	BULLY
CREST	CHEAT	CLEFT	CHEST
GLIDE	GUISE	GRIME	GUIDE
MARRY	MERCY	MURKY	MERRY
PEACE	PLATE	PHASE	PLACE
SMACK	SHARK	SPARK	SHACK
SMALL	SHAWL	SNAIL	SHALL
STAVE	SHAPE	SPADE	SHAVE
STEER	SHEAR	SMEAR	SHEER
SPARK	STALK	SLACK	STARK
SHONE	STOKE	SLOPE	STONE
SWORE	STOVE	SMOKE	STORE
SCRAP	STRIP	SYRUP	STRAP
SHEET	SWEAT	SPENT	SWEET
Experiment 3 (same position): Position 4 → Position 4			
BIRCH	BERTH	BURGH	BIRTH
BLEND	BREED	BREAD	BLEED
BROAD	BLOOD	BLOND	BROOD
CHECK	CREEK	CREAK	CHEEK
CLONE	CHOSE	CHOKE	CLOSE
CROSS	CHOPS	COOKS	CROPS
CURLY	CARRY	CORNY	CURRY
GLOBE	GROVE	GOOSE	GLOVE
SHAME	SCARE	STAGE	SHARE
SHIFT	SKIRT	SPILT	SHIRT
SHOVE	SCORE	SMOKE	SHORE
SHOWN	SCORN	SPOON	SHORN
SPECK	SNEAK	SLEEK	SPEAK
SPIKE	SWINE	SLIDE	SPINE
WHINE	WRITE	WAIVE	WHITE
Experiment 3 (adjacent position): Position 2 → Position 3			
ANKLE	AGILE	AISLE	ANGLE
BENCH	BATCH	BOTCH	BEACH
BOOTS	BAITS	BEETS	BOATS
CAGED	CRIED	CODED	CARED
CHOSE	CAUSE	CURSE	CHASE
CREED	CITED	CANED	CRIED
FILES	FRIES	FUMES	FIRES
Experiment 3 (adjacent position): Position 2 → Position 3 (*continued*)			
HERDS	HANDS	HOODS	HEADS
LORDS	LANDS	LENDS	LOADS
PERCH	PATCH	PINCH	PEACH
PIPED	PLIED	POKED	PILED
POACH	PUNCH	PITCH	POUCH
PULSE	PROSE	PHASE	PURSE
SHIPS	SOAPS	SNAPS	SHOPS
TILED	TRIED	TAXED	TIRED
Experiment 3 (adjacent position): Position 4 → Position 3			
BLOCK	BLEAK	BLINK	BLACK
BLINK	BLEAK	BLOCK	BLANK
BLISS	BLUES	BLOWS	BLESS
CRICK	CREAK	CREEK	CRACK
DITTY	DIARY	DIZZY	DIRTY
GRUNT	GREAT	GREET	GRANT
HANDY	HAIRY	HAPPY	HARDY
PARTS	PAWNS	PAGES	PANTS
SPELL	SPOIL	SPOOL	SPILL
STILL	STEAL	STEEL	STALL
STORK	STEAK	STINK	STARK
STOUT	START	STINT	STRUT
HOMES	HOWLS	HORNS	HOLES
THYME	THREE	THOSE	THEME
THOSE	THREE	THYME	THESE
Experiment 3 (two-letter distant position): Position 2 → Position 4			
ABOVE	ADORE	ALONE	ABODE
BONES	BUNKS	BANKS	BONUS
CHANT	CRAFT	COAST	CHART
GOATS	GLASS	GEARS	GOALS
LINKS	LENDS	LANDS	LINES
SHADE	SKATE	STAGE	SHAKE
SLEET	SPENT	SCENT	SLEPT
SLICE	SMILE	SHINE	SLIME
SNARE	SKATE	SUAVE	SNAKE
SPADE	SCALE	SHAME	SPACE
SPARK	SNACK	SLACK	SPANK
STEMS	SPECS	SHEDS	STEPS
STOVE	SLOPE	SCOPE	STOLE
STORY	SNOWY	SMOKY	STONY
SWEET	SPENT	SCENT	SWEPT
Experiment 3 (two-letter distant position): Position 4 → Position 2			
ABIDE	ARISE	AGILE	ASIDE
CRASS	COALS	CHAOS	CLASS
ELECT	EXERT	EVENT	ERECT
GLASS	GEARS	GOATS	GRASS
SCANT	SHALT	SHAFT	SLANT
SUAVE	SCALE	SPARE	SLAVE
SALES	SILOS	SILKS	SOLES
SLATE	SHAPE	SHAME	SPATE
SLICE	SWIPE	SWINE	SPICE
SHIRE	SWIPE	SLICE	SPIRE
SUITE	SWIPE	SWINE	SPITE
SMOKE	SLOPE	SNORE	SPOKE
SCALE	SLATE	SPADE	STALE
SCARE	SKATE	SUAVE	STARE
SPOON	SHOWN	SCORN	SWOON

Note. The stimuli for the similar-context conditions in Experiment 2 were identical to those in Experiment 1; as such, only stimuli for the dissimilar-context conditions in Experiment 2 are presented above.

Appendix B

Match Computations With Spatial Codes

Spatial Codes

A spatial code can be written as a vector consisting of *n* elements, where *n* is the number of letters in the input string, and the values in the vector represent the activities of the corresponding letter nodes. Spatial codes always use a monotonically descending series to code letter position. Suppose, for simplicity, that a four-letter word is coded by the set of activities {4, 3, 2, 1}; for example, in the word STOP, the *S* letter node is coded by an activity of 4, the *T* letter node by an activity of 3, and so on.

Equilibrium Values of the Weights Connecting Letter and Word Nodes

We suppose that one effect of learning is that each word node "knows" which letters to attend to (i.e., which letters make up the particular word that it codes). Thus, the word node that codes STOP only considers inputs from the letter nodes for *S*, *T*, *O*, and *P*. For the *i*th word node, this set of letters is denoted L_i, and the number of letters in this set (i.e., the length of the word) is denoted l_i (e.g., $L_{\text{STOP}} = \{\text{S, T, O, P}\}$, and $l_{\text{STOP}} = 4$). The weight between a letter node and a word node is equivalent to the value of that letter node's activity in the spatial code for that word; for example, the weight from the *S* letter node to the STOP word node is $z_{\text{S,STOP}} = 4$. Davis (1999) describes how the SOLAR model is able to self-organize so as to learn appropriate weights following exposure to a vocabulary.

Computation of Match Values

Each word node computes a match value that describes the degree to which the word that it codes matches the current input stimulus. One method for computing match values is as follows (others are described in Davis, 2004). The first step in computing this match value is simply to count the number of letters that the input stimulus shares with the comparison word in any position (this corresponds to the number of input signals that are received by the node that codes this word); this is denoted C_i. The next step involves computing a set of signal-weight differences. For each of the elements in the set L_i, a difference d_{ji} is computed by subtracting from s_j (the activity of the *j*th letter node) the corresponding weight z_{ji}, that is,

$$d_{ji} = s_j - z_{ji}. \tag{1}$$

The congruence (or *harmony*) of this set of differences is calculated as follows

$$H_i = \Sigma \frac{|d_{ji} - \mathbf{D}|}{l_i}, \tag{2}$$

where **D** is the average difference score (across the set L_i). A low value of H_i indicates a set of signal-weight differences that are relatively harmonious, implying that the letters in the input stimulus are arrayed in the same relative positions as they are in the word coded by the *i*th word node.

A match value, M_i, can then be computed as follows

$$M_i = \frac{(C_i - H_i)}{l_i}. \tag{3}$$

The maximum value of M_i is 1, which is found when $C_i = l_i$ and $H_i = 0$—that is, when all of the letters in the word coded by the *i*th word node are present in the input stimulus, and they each occur in the correct position relative to each other. The minimum value of M_i is 0, which occurs when $C_i = 0$ (and thus $H_i = 0$; i.e., when none of the letters in the word coded by the *i*th word node is present in the input stimulus). Thus the set of Equations 1–3 produces a match value that lies between 0 and 1.

To illustrate these computations, consider the match values that are computed by the STOP word node for the inputs STOP, STEP, SOAP and SNAP. A perfect match (STOP) results in four common letters ($C_i = 4$), all in the correct relative position ($H_i = 0$), and thus the match value is $4/4 = 1$. A substitution neighbor like STEP shares three letters with the comparison word ($C_i = 3$), and these are all in the correct relative position ($H_i = 0$), and thus the match value is $3/4 = .75$. Similarly, a double-substitution neighbor like SNAP shares two common letters with the comparison word ($C_i = 2$), and these are all in the correct relative position ($H_i = 0$), and thus the match value is $2/4 = .5$. The once-removed neighbor SOAP shares three letters with the word STOP ($C_i = 3$), but one of these (the *O*) is shifted leftward relative to the other letters (hence $H_i = .25$), which results in a match value of $(3 - .25)/4 = .6875$. This is a much better match than that for a double-substitution neighbor like SNAP, but a poorer match than that for a substitution neighbor like STEP, just as is suggested by the LM data discussed in the present article. That is, the letter *O* counts in the computation of similarity, even though it occurs in different positions in SOAP and STOP.

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