Visual similarity effects on masked priming

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Abstract We investigated the role of the visual similarity of masked primes to targets in a lexical decision experiment. In the primes, some letters in the target (e.g., A in ABANDON) had either visually similar letters (e.g., H), dissimilar letters (D), visually similar digits (4), or dissimilar digits (6) substituted for them. The similarities of the digits and letters to the base letter were equated and verified in a two-alternative forced choice (2AFC) perceptual identification task. Using targets presented in lowercase (e.g., abandon) and primes presented in uppercase, visually similar digit primes (e.g., 484NDON) produced more priming than did visually dissimilar digit primes (676NDON), but little difference was found between the visually similar and dissimilar letter primes (HRHNDON vs. DWDNDON). These results were explained in terms of task-driven competition between the target letter and the visually similar letter.

Keywords Word recognition · Lexical processing · Repetition priming

People are remarkably efficient at recognizing letters, despite the variability in surface form—for instance, A, Ā, and a are all readily recognized as instances of the letter “a,” across their variations in size, font, and case. Consistent with this observation, most current visual word recognition models assume that the letter representations subserve word recognition are “abstract letter identities.” This assumption is shared both by models adopting the interactive-activation framework (originally put forward by McClelland & Rumelhart, 1981)—such as the dual-route cascaded (DRC) model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), the multiple read-out model (MROM; Grainger & Jacobs, 1996), the spatial-coding model (SCM; Davis, 2010), and various “open-bigram” models (e.g., SERIOL: Whitney, 2001, 2008; or the parallel open-bigram model: Grainger & Van Heuven, 2004)—and those that eschew the activation metaphor and instead regard visual word recognition as a Bayesian inference-making process—such as the Bayesian Reader (Norris, 2006), and its successors, the noisy slot model (Norris, Kinoshita, & van Casteren, 2010) and the noisy-channel model (Norris & Kinoshita, 2012). In the latter frameworks, the reader is characterized as making an optimal Bayesian inference in mapping noisy perceptual evidence onto a word that best matches the input.

The topic investigated in the present article concerns the role of the visual similarity of letters in the early stages of visual word recognition in skilled readers. We first present a brief review of the masked-priming literature that seems to suggest two conflicting views, with one group of studies suggesting that the visual similarity of the prime and target letters has no bearing on priming, and the other suggesting that it does. We will argue, however, that the conflict is more apparent than real, and that these studies do not address the question of whether the visual similarity between letters matters. We then present an experiment, testing whether a prime containing letter substitutions with visually similar letters produces more priming than a prime containing visually dissimilar letter substitutions.

As is apparent from studies that have examined the identification of isolated letters (for a recent review, see Mueller & Weidemann, 2012), letters such as E and F, and C and O, are visually similar and confusable with each other. However, in current models of visual word recognition, the letter representations that feed into lexical representations are assumed to be abstract, and the visual similarity between letters plays a
minimal role in word recognition itself. This is consistent with studies based on masked priming that have shown that the visual similarity of the letters in the prime and the target has no impact on the size of the identity priming. In the masked-priming procedure developed by Forster and Davis (1984), which has been adopted as the standard in visual word recognition studies using the Latin alphabet, the prime is presented in lowercase letters and the target in uppercase, so as to avoid physical overlap (e.g., table–TABLE). Capitalizing on this, Bowers, Vigliocco, and Haan (1998) elegantly demonstrated that the letter representations supporting word recognition are abstract. They compared the sizes of the identity-priming effects for words consisting of letters that are visually similar in uppercase and lowercase (e.g., kiss–KISS) and words consisting of letters that are visually dissimilar across cases (e.g., edge–EDGE). In both a lexical decision task and a noun–verb decision task, visual similarity had little effect on the size of priming, leading Bowers and al. to conclude that masked priming in word recognition is based on abstract letter identities.1 Perea, Abu Mallouh, and Carreiras (2013) recently extended this finding to Arabic. Although Arabic does not have uppercase and lowercase letters, it has an intricate system of allography. Arabic is written cursively from right to left and has 28 letters. Two variables interact to determine which allograph is used for a given letter. These are the position of the letter in the word—initial, medial, or final—and the presence or absence of a ligature (i.e., whether the letter is connected) to the preceding letter. Like Hebrew, another Semitic language, words in Arabic can be decomposed into a three-letter consonantal root that conveys the basic meaning (e.g., ktb for “marking/writing”) and a phonological word pattern consisting of a sequence of vowels (or a sequence of vowels and consonants), which is embedded in the root. Perea et al. (2013) created primes by substituting a word pattern letter with either a letter that kept the same ligation pattern as in the target word (visually similar) or one that altered the ligation pattern (visually dissimilar). The magnitude of priming did not differ between the “same-ligation” and “different-ligation” conditions, indicating that the visual similarity of allographs did not influence masked priming.

In contrast to these studies, studies using “leet” primes—letter strings that contain digits (or symbols) resembling letters embedded in a letter string: for example, M4T3R14L for MATERIAL—have shown that priming is determined by the visual similarity between the prime and target. Perea, Duñabeitia, and Carreiras (2008; see also Carreiras, Duñabeitia, & Perea, 2007) contrasted leet primes containing digits that were visually similar to the replaced letter (the “related leet” primes; e.g., M4T3R14L) and primes containing digits that did not resemble the replaced letter (the “control leet” primes; e.g., M5T6R28L), and found that whereas the related leet primes facilitated the recognition of the target almost as much as the identity primes (e.g., MATERIAL), the control leet primes produced little more facilitation than did control letter primes (e.g., MOTURUOL). These results indicate that the visual similarity between the digit and the replaced letter was critical in producing priming.

On the surface, these two sets of findings appear to suggest a contradiction: On the one hand, studies manipulating the visual similarity of allographs (uppercase and lowercase letters in English, or ligation-dependent allographs in Arabic) revealed no role for visual similarity in modulating priming; on the other hand, studies using leet primes showed that the visual similarity of the digit/symbol is the key factor responsible for priming. We suggest, however, that the contradiction is more apparent than real. The two sets of studies differ in the ways that visual similarity was manipulated. Specifically, in the allograph studies, the manipulation concerned the visual similarity between different instances of the same letter identity (A, a, A, etc.) in the prime and target—that is, between tokens that mapped onto the same letter type. In these cases, the form of the letter does not matter, indicating that visual word recognition is based on abstract letter identities.

In contrast, in the leet-priming studies, the visual-similarity manipulation concerned similarity between an input and a letter type. To the extent that different letter identities are defined by their shape, for a visual input (e.g., the digit 4 or 8, or the symbol €) to be taken as an instance of a particular letter (e.g., A, B, or E), it must visually resemble a manifestation of that letter. Here, then, the critical manipulation involves the similarity of the substituted digit to the original letter, and form does matter (e.g., 4 resembles A, but 5 does not).

The fact that masked priming is insensitive to the similarity of the form of the allograph letters in the prime and target follows naturally from the idea that the prime letters contribute evidence for the identity of the word, and the letters in the target carry on contributing further evidence. An uppercase A and a lower case a provide equally good evidence for any word containing the abstract letter identity representing the first letter of the alphabet. This idea is formalized in Norris and Kinoshita’s (2008) account of masked priming, in which

1 Bowers et al. (1998) further reported that in contrast to the word recognition tasks, in single-letter recognition tasks (e.g., the alphabet decision task), little masked priming was apparent for abstract letter identities. This conclusion seems to have been premature, because robust priming effects for abstract letter identities have been found in the same–different task, which is not subject to the stimulus–response mapping strategy in other letter recognition tasks that have been used (see Kinoshita & Kaplan, 2008, for details).
masked-priming effects are explained in terms of the prime and the target both contributing evidence to the decision required by the task. Norris and Kinoshita (2008, Exps. 2 and 3) studied letter similarity effects using the same–different task. In this task, participants are instructed to decide whether the target is the same as or different from the referent that is presented in advance for 1 s. When the referent was always in the opposite case from the target (the “cross-case” same–different task) and participants were instructed to respond “Same” irrespective of the difference in case (e.g., responding “Same” to the target A and the referent a), the visual similarity of the masked prime and the target (e.g., a and A are dissimilar; c and C are similar) did not modulate the size of priming. That is, priming appeared to be driven by abstract letter identity, and not by the physical form of the letters. The same prime–target pairs showed a completely different pattern when priming when the task was changed. When participants were instructed to respond “Same” only if the referent and the target were the same letter in the same case (e.g., responding “Same” to the target A and the referent A, and responding “Different” to the target A and the referent a), priming was abolished for the visually dissimilar prime–target letter pairs. These results led Norris and Kinoshita to argue that priming was not an automatic consequence of the visual similarity between the prime and target, but is guided by the demands of the task.

So, in the tasks of lexical decision or same–different comparisons of letter identity (letter name), priming is determined by abstract letter identity. The letters a and c in the prime contribute the same amount of evidence toward the abstract letter identities A/a and C/c, respectively, irrespective of the similarity of a form to the letter in the target (i.e., a is dissimilar in form to A; c is similar in form to C). However, in the case of leet priming, there is competition between the different possible interpretations of the letters in the prime for which digits are substituted (the similarity of the digits to the letter—i.e., the similarity of 4 to A, as compared with 5 to A). This changes the evidence that is being contributed to the abstract representation of the letter a/A. The digit 5, being less similar to A than is 4, will contribute less evidence for the abstract letter a/A. The similarity between the digit and the letter therefore modulates priming. In the experiment to be reported here, we focused on trying to understand exactly how this competition process operates. Specifically, we compared leet priming with an analogous manipulation of similarity in which similar or dissimilar letters were substituted for the letters. Would a visually similar letter (e.g., H substituting for A) produce more priming than a visually dissimilar letter (e.g., D substituting for A)?

Before turning to this experiment, we should note some methodological differences between the allograph experiments and the leet-priming experiments that may have contributed to the disparate results. One is the length, and hence the neighborhood density, of the target words used. The allograph studies (e.g., Bowers et al., 1998) used short words (which are necessarily in dense neighborhoods), whereas the leet-priming studies (e.g., Perea et al., 2008) used six- to eight-letter (Spanish) words. Given that there is evidence that orthographic priming effects in lexical decision are small and weak for short words in dense lexical neighborhoods (the “target density constraint”; Forster, Davis, Schoknecht, & Carter, 1987), it may be that the allograph studies using shorter words were not sensitive enough to pick up an effect of visual similarity on masked priming. Second, and potentially more important, in the leet-priming study by Perea et al. (2008), both the prime and target were presented in uppercase letters (though in different-size fonts: 10-point Courier for the prime and 12-point Courier for the target, so that the physical overlap was not complete), so it is arguable that the “visually similar” leet prime and the target were overall physically more similar than in the allograph studies, in which the prime and target were presented in different cases (consider, e.g., M4T3R14L–MATERIAL vs. material–MATERIAL). It should be noted that some data argue against this possibility. Kinoshita and Norris (2011, Exp. 1) observed that the size of the identity-priming effects in lexical decision for word targets presented in mixed Case (e.g., wEaPoN, presented in Courier New 12-point font) did not differ when the prime presented in lowercase letters was in the same font as the target (e.g., weapon, in 12-point Courier New) or in a different font (e.g., weapon in Arial 10-point font). That is, the greater physical similarity between the letters in the prime and the target did not impact the size of priming, and by extension, Perea et al.’s (2008) leet-priming results are also unlikely to be due to low-level physical similarity. Nonetheless, it is possible that some or all of these methodological differences in combination may explain why visual similarity modulated priming in the leet-priming studies but not in the allograph studies.

The aim of the present study was to investigate the effects of visual similarity between letters on priming. Would substituting visually similar letters for the letters in a prime (e.g., A with H, or B with R) produce more priming than substituting visually dissimilar letters for them (e.g., A with D, or B with W), as in the leet-priming effect? To test this, we used four critical prime conditions resulting from a factorial combination of visual similarity (similar vs. dissimilar) and substitution type (digit vs. letter). In the visually similar digit prime, the critical letters were replaced with visually similar digits (e.g., A/4, B/8, to produce 484NDON–abandon), and in the visually dissimilar digit condition, the critical letters were replaced with visually dissimilar digits (e.g., 676NDON–
abandon). On the basis of the leet-priming results reported previously, we expected the visually similar digit primes to produce greater priming than the dissimilar digit primes. The key comparison involved the two letter substitution prime conditions. In the visually similar letter prime, the critical letters were replaced with visually similar letters (e.g., A/H, B/R, for HRHNDON—abandon), and in the visually dissimilar letter prime, the critical letters were replaced by visually dissimilar letters (e.g., DWDNDON—abandon).

In the experiment, we also wished to eliminate the potential confounds between the allograph studies and the leet-priming studies described above. To this end, the visual similarity manipulation was applied to the same base letters; that is, the same letters in the prime were replaced with both visually similar/dissimilar digits (leet prime) and letters. Also, we used seven-letter-long target words (which have few neighbors), so as to maximize the opportunity for observing orthographic priming effects. To minimize physical overlap in the stimuli, we presented the prime and target in different cases.

In addition, to rule out the possibility that any difference between the digits and letters might be attributed to a stronger manipulation of visual similarity for one item type (e.g., 4 may be more visually similar to A than H is to A), we took measures to equate the similarity of the letter and digit substitutions to the base letter. We first consulted a number of letter confusion matrices (reviewed in Mueller & Weidemann, 2012) to select letters that were very confusable (for the similar-letter condition) and were least confusable (for the dissimilar-letter condition) with the base letter. We then presented these letters and digits as distractors and the base letter as the target in a two-alternative forced choice (2AFC) identification task. We used the identification data to select replacement letters and replacement digits, so that they were matched on confusability with the target letters. (The data from this identification task are presented in Appendix A.) We repeated the 2AFC identification task with the participants in our critical masked-priming experiment, to ensure that they also found the substitution digits and letters to be equally confusable with the target letter when all characters were presented singly.

**Method**

**Participants**

A group of 37 students from Macquarie University participated in the experiment in return for course credit.

**Design**

For the experiment, we used the lexical decision task and manipulated the factor Prime Type (identity, letter similar, letter dissimilar, digit similar, digit dissimilar, and all letters different) within subjects. The dependent variables were response latency and error rate.

**Materials**

The critical stimuli were 120 seven-letter words, containing at least three occurrences of the letters A, I, S, or B. These letters were chosen because they had been used in previous leet-priming studies (e.g., Kinoshita & Lagoutaris, 2010; Perea et al., 2008; Perea, Duñabeitia, Pollatsek, & Carreiras, 2009) and had digits that resembled them (A/4, I/1, S/5, and B/8). In addition to the visually similar digits, for each of the letters, we chose a visually dissimilar digit (A/6, I/2, S/7, and B/7), a visually similar letter (A/H, I/L, S/E, and B/R), and a visually dissimilar letter (A/D, I/G, S/D, and B/W). These letters were chosen from a wider range of items selected by consulting Mueller and Weidemann’s (2012) letter confusion matrices, which were then tested in a 2AFC identification task conducted to equate the digits and letters on their degrees of similarity to the base letter. The procedure of the 2AFC perceptual identification task was identical to that conducted in the main experiment described below, except that the targets were presented for 53 ms. The data for the pilot 2AFC perceptual identification task are presented in Appendix A.

The 120 critical words were selected from the English Lexicon Project (ELP) database (Balota et al. 2007, available at http://ellexicon.wustl.edu/) and had a maximum of two orthographic neighbors (range 0–2, mean 0.4), as defined by the N metric (Coltheart, Davelaar, Jonasson, & Besner, 1977). This was done to maximize the opportunity for observing orthographic priming effects, since short words from dense lexical neighborhoods show small priming effects in the lexical decision task. We chose words with a minimum mean lexical decision accuracy of .88 (mean = .97). This was done to ensure that the stimuli were known to the participants as words. The words ranged in frequency (15–206, mean = 49.1 per million, based on Kučera & Francis, 1967; 0.29–194.8, mean = 22.5 per million, based on Subtlex frequency—Brysbaert & New, 2009; 6.57–12.42, mean = 9.4 log HAL frequency). Examples are abandon and optimal.

For each word, six primes were generated. The critical prime conditions were a factorial combination of the factors Similarity (similar vs. dissimilar) and Substitution Type (letter vs. digit). Each target word contained the letters A, I, S, or B.
Within each word, each occurrence of these four letters was then replaced with one of the four substitution characters. In the **similar-letter** prime, the letters were replaced with letters that were visually similar to the target letters: H for A, L for I, E for S, and R for B—for example, HRHNDON for ABANDON. In the **dissimilar-letter** prime, the letters were replaced with letters that were visually dissimilar to the target letters: D for A, G for I, D for S, and W for B—for example, DWDNDON for ABANDON. In the **similar-digit** prime, the letters were replaced with digits that were visually similar to the target letters: 4 for A, 1 for I, 5 for S, and 8 for B—for example, 484NDON for ABANDON. In the **dissimilar-digit** prime, the letters were replaced with digits that were visually dissimilar to the target letters: 6 for A, 2 for I, 7 for S, and 7 for B—for example, 676NDON for ABANDON. The remaining two primes were an **identity** prime—for example, ABANDON for ABANDON—and an **all-letter-different (ALD)** prime, which was a different word that had no letters in common with the target—for example, PRODUCT for ABANDON. All of the primes were presented in uppercase letters, and the targets were presented in lowercase letters. The target words and primes are listed in Appendix B.

The 120 target words were divided into six sets of 20, matched on mean frequency. Six list versions were constructed for the purpose of counterbalancing the assignments of sets to the six prime types using a Latin square, so that within a list, each target word occurred only once, and across the six lists, each word appeared in each of the six prime conditions once.

In addition to the critical target words, 120 seven-letter nonwords were selected from the ELP database. They were all orthographically legal and matched item-by-item to the words for N—for example, ABEMISK, FENGILE. The same six types of primes used with the word targets (identity, similar letter, dissimilar letter, similar digit, dissimilar digit, and all letters different) were generated for the nonword targets, according to the same procedure. Six list versions were constructed for the purpose of counterbalancing the assignments of sets to the six prime types using a Latin square, so that within a list, each target nonword occurred only once, and across the six lists, each nonword appeared in each of the six prime conditions once.

In addition, 12 practice and initial buffer items were presented, which were selected according to the same criteria as the test stimuli. These items were not included in the analysis.

**Apparatus and procedure**

Participants were tested in groups of one to four, seated approximately 60 cm in front of a CRT monitor, upon which the stimuli were presented. Each participant completed 240 test trials consisting of 120 word and 120 nonword trials, presented in two half-blocks (with each half-block containing equal numbers of word and nonword trials and equal numbers of items from the different prime conditions), with a self-paced break between the blocks. A different random order of trials was generated for each participant.

**Lexical decision task** Participants were instructed at the outset of the experiment that on each trial they would be presented with a letter string in lowercase letters following a warning signal consisting of # signs, and that their task was to decide whether the letter string was a word or a nonword as quickly and accurately as possible. No mention was made of the presence of primes. Participants were instructed to press a key on a response pad marked “+” for “Word” and a key marked “-” for “Nonword” responses.

The stimulus presentation and data collection were achieved through the use of the DMDX display system, developed by K. I. Forster and J. C. Forster at the University of Arizona (Forster & Forster, 2003). Stimulus display was synchronized to the screen refresh rate (13.3 ms).

Each trial started with the presentation of a forward mask, consisting of seven # signs, for 500 ms in the center of the screen. It was replaced by the prime in uppercase letters, presented for 40 ms, then by the target, presented in lowercase letters for a maximum of 2,000 ms, or until the participant’s response. (Note that it was necessary to present the prime in uppercase letters, because the letters that the digits resembled were all uppercase letters—e.g., 4–A, 8–B, etc.) The forward mask and primes were presented in Courier New 10-point font, and the target was in Courier New 12-point font, so that the target effectively backward-masked the prime. Participants were given feedback (the message “Wrong response” presented on the screen) only when they made an error.

**2AFC identification task** Immediately after the lexical decision task, participants performed an identification task. The purpose of this task was to verify the perceived similarity of the substituted letter/digit to the target letter. On each trial, following a forward mask consisting of three # signs presented for 500 ms, a letter or a digit was presented flanked by % signs (e.g., “%A%”) for 40 ms, and followed immediately by a backward mask consisting of three # and @ signs overlaid on each other. Two alternatives, one a target (e.g., A) and the other a distractor (e.g., 4), were presented simultaneously to the right and left of the backward mask, and remained on the screen until the participant’s response. Participants were instructed that they had 10 s to indicate which of the two alternatives had been presented as the target, by pressing a key corresponding to its location (left or right). No feedback was
Results

Lexical decision task

We analyzed the response times (RTs) from correct trials and the error rates for word targets using a linear mixed-effects model (Baayen, 2008). We did not analyze the nonword data, since they are insensitive to masked priming in the lexical decision task (see Norris & Kinoshita, 2008, for an explanation). The preliminary treatment of the correct RT data for this analysis was as follows. First, we examined the shape of the RT distribution (a total of 4,187 data points) and applied an inverse transformation (1/RT) to approximate a normal distribution, in order to meet the distributional assumption of the linear mixed-effects model. (We used the inverse transformation rather than the log transformation because the inverse transformation approximated the normal distribution better.) We excluded trials with RTs shorter than 300 ms (six data points). This cutoff for outliers was determined by inspecting the Q–Q plots of the inverse-transformed RTs. The dependent variable used in our analysis was “invRT,” defined as −1,000/RT: We multiplied 1/RT by −1,000 to maintain the direction of the effects (so that a larger invRT meant a slower response), and to avoid too many decimal places. We used the lme4 (Version 0.999999-2; Bates, Maelchler, & Bolker, 2013) package, as implemented in R Version 3.0.0 (R Development Core Team, 2013), to carry out the linear mixed-effect model analysis, treating Subjects and Items as crossed random factors. The p values reported here were estimated using the Markov-chain Monte Carlo sampling method (with the default 10,000 iterations), implemented in the languageR package (Version 1.4; Baayen, 2011).

Table 1 shows the mean RTs in the six prime conditions for the word targets as well as the nonword targets.

We first tested a statistical model that included, as fixed factors, Prime Type (referenced to the ALD prime), Log HAL Frequency, and prevRT (RT on previous trial), with the

Table 1 Mean decision latencies (RTs, in milliseconds) and percent error rates (%E) in the experiment (lexical decision task)

| Prime type          | Example  | RT   | %E  |
|---------------------|----------|------|-----|
| **Word target (abandon)** |          |      |     |
| Identity            | ABANDON  | 504  | 4.1 |
| Similar letter      | HRHNDON  | 519  | 6.4 |
| Dissimilar letter   | DWDNDON  | 527  | 5.7 |
| Similar digit       | 484NDON  | 509  | 4.7 |
| Dissimilar digit    | 676NDON  | 530  | 6.9 |
| ALD                 | PRODUCT  | 557  | 5.7 |
| **Nonword target (faxisum)** |      |      |     |
| Identity            | FAXISUM  | 594  | 5.0 |
| Similar letter      | FHXLEUM  | 594  | 5.0 |
| Dissimilar letter   | FDXGDUM  | 597  | 4.6 |
| Similar digit       | F4X15UM  | 593  | 6.2 |
| Dissimilar digit    | F6X27UM  | 606  | 6.4 |
| ALD                 | ICQUIDE  | 603  | 6.2 |

The primes were presented in uppercase letters in Courier New 10-point font, and the targets were presented in lowercase letters in Courier New 12-point font, so that the target effectively backward-masked the prime. Subjects Intercept (37) and Target Intercept (120) as crossed random factors: invRT ~ Prime type + Log HAL frequency + prevRT + (1|subject) + (1|target). To examine the effect of the previous-trial RT, trials on which an error had been made on the previous trial were excluded from the analysis, resulting in 3,974 data observations. The model shows that the effect of log HAL frequency was significant, t = −6.875, p < .0001, as was prevRT, t = 12.975, p < .0001. Referenced to the ALD prime condition, all prime conditions were significantly faster: identity t = −10.494, p < .0001; similar letter t = −6.497, p < .0001; dissimilar letter t = −4.968, p < .001; similar digit t = −9.743, p < .001; and dissimilar digit t = −5.014, p < .001. Referenced to the identity-prime condition, the 5-ms difference from the similar-digit prime condition was not significant, t = 0.794, p = .418, but the 15-ms difference from the similar-letter prime condition was, t = 3.953, p < .0001.

We then analyzed the critical four experimental conditions in a 2 × 2 factorial design with Similarity (similar vs. dissimilar) and Substitution Type (letter vs. digit) as fixed factors. The similarity effect was significant, t = −4.396, p < .0001, with similar primes facilitating responses to the targets. The

2 We also tested models containing the same fixed factors and subject and item random slopes on the Prime Type factor. Since the model with subject and item random slopes did not converge and the model with subject random slopes did not produce a better fit than the model with random intercepts [χ²(20) = 25.389, p = .1869], we report the simpler model with random intercepts.
substitution type effect was also significant, $t = 2.216$, $p < .026$, with the digit primes producing faster responses to the targets. Importantly, the interaction was significant, $t = 2.131$, $p < .034$, indicating that the similarity effect was greater for the digit primes than for the letter primes. Individual comparisons indicated that the 21-ms similarity effect for the digit primes was significant, $t = -4.448$, $p < .001$, but the 8-ms effect for the letter primes was not, $t = -1.655$, $p = .0982$.

Error rates were analyzed using the logit linear mixed-effects model (Jaeger, 2008) with Prime Type and Log HAL Frequency as fixed factors and the Subject Intercept and Word Intercept as crossed random factors. Log HAL frequency significantly reduced the error rate, $z = -6.061$, $p < .0001$. Referenced to the ALD prime, none of the prime conditions differed significantly from this condition. The analysis of the critical four prime conditions showed that neither the effect of similarity ($z = -1.023$, $p = .306$) nor substitution type ($z = 0.229$, $p = .818$), nor the interaction between the two ($z = 1.614$, $p = .106$), was significant.

2AFC identification task

Averaged across the four target letters (A, I, S, B), the mean error rates were 44.15 % for the similar-letter distractor, 41.17 % for the dissimilar-letter distractor, 43.52 % for the similar-digit distractor, and 41.38 % for the dissimilar digit distractor. We analyzed the error rates using the logit linear mixed-effects model (Jaeger, 2008), with Distractor Type (letter vs. digit) and Visual Similarity (similar vs. dissimilar) as fixed factors and Subject Intercept (37) and Target Intercept (4) as crossed random factors. Distractor type was nonsignificant, $z = 0.168$, $p = .866$, but similarity was significant, $z = 2.214$, $p < .027$. We found no interaction between the two, $z = 0.364$, $p = .716$. Thus, the identification data confirmed that the letter and digit distractors were equated on their perceived similarity to the target letter, with the similar distractors being perceived to be more similar to the target than the dissimilar distractors.

Discussion

The results were clear cut, indicating a dissociation between the effects of visual similarity for digit primes and letter primes. Replicating previous leet-priming studies, the primes containing visually similar digits (e.g., 484NDON for ABANDON) produced robust priming, which was greater than that produced by the primes containing visually dissimilar digits (e.g., 676NDON for ABANDON). The priming effect produced by visually similar digit primes was equal in size to the identity-priming effect (ABANDON–abandon). It should be noted that, unlike the previous leet-priming studies that had presented the prime and target in the same case (both uppercase), the targets were presented in lowercase letters; hence, the leet-priming effect observed here cannot be attributed to a physical overlap between the prime and target. In contrast to the digit primes, the letter primes showed little effect of visual similarity: Similar-letter primes (e.g., HRHNDON) produced no more priming than did dissimilar-letter primes (e.g., DWNDN). The comparison to the identity prime condition further confirmed that the visually similar letter primes produced significantly less priming than did the identity primes. The 2AFC identification task indicated that the dissociative effect of visual similarity was not due to the similar-digit distractor being perceptually more similar than the similar-letter distractor to the base letter: The letter and digit distractors (e.g., H and 4, respectively) used in the masked prime were perceived as being equally confusable with the base letter (e.g., A).

As far as we are aware, this was the first study to examine the effects of visual similarity on masked priming with substituted-letter primes. Unlike the digit primes, which showed greater priming for visually similar items (replicating the previous findings of leet priming), visual similarity had little impact on the priming produced by the substituted-letter primes. How can this dissociation be explained, and what are the implications for the current models of visual word recognition?

One potential solution to explaining this dissociation would be to propose that a top-down feedback mechanism, available selectively for letter stimuli, normalizes the shape of the ambiguous form. Indeed, such a view was proposed by Perea, Duñabeitia, Pollatsek, and Carreiras (2009) to explain their findings using the same different match task. In their study, primes containing leet digits (e.g., V35Z3D) facilitated matches for letter-string targets (e.g., VESZED), but primes containing leet letters (e.g., 9ES7E2) did not facilitate matches for digit-string targets (e.g., 935732). This top-down feedback account was, however, ruled out by Kinoshita and Lagoutaris

3 Recently, Perea and Panadero (2013) reported a similar absence of letter similarity effect with nonword targets. The authors found that adults and typically developing young readers were insensitive to the visual similarity of the substituted letter in a nonword target—e.g., viocin (in which the letter $t$ is visually similar to the original letter $l$) was no more difficult to reject as a nonword than viocin (in which the letter $c$ is visually dissimilar to $l$). Unlike in the present study, Perea and Panadero defined letter similarity in terms of whether the target and distractor letter shared an ascender/descender/neutral feature, however, and the confusability of the target and distractor letters was not verified empirically.
(2010), who showed that the asymmetry in leet priming was due to the difference in the ease of maintaining in visual working memory a long reference sequence of random digits (e.g., 935732) versus a well-formed pseudoword (e.g., VESZED). In order to perform a same–different match, the target must be compared against a representation of the reference string maintained in visual working memory, the capacity of which is generally assumed to be four objects (Vogel, Woodman, & Luck, 2001). Kinoshita and Lagoutaris thus reasoned that it would be difficult to maintain an accurate representation of a random sequence of six digits, but it may be possible to maintain a sequence of six letters that form a pseudoword by means of chunking. Consistent with this theory, the size of the identity-priming effect was also reduced for the six-digit strings relative to the six-letter pseudowords. Critically, Kinoshita and Lagoutaris showed that the asymmetry in leet priming was eliminated when (1) the reference string was a short sequence of four digits (e.g., 2157) or a four-letter pseudoword (e.g., MISF), and (2) the reference string was a long sequence of six random digits (e.g., 214637) or a six-letter sequence of random letters (e.g., OIAUEQ). These findings provide no support for the view that a top-down feedback mechanism is available selectively for letter stimuli.

To explain the present finding of the dissociative effect of visual similarity, we suggest that the key difference between the digit and letter primes is the presence of a (letter) competitor. In the case of the visually similar digit primes (e.g., 4), the target letter (e.g., A) is the best-matching letter. This is not the case for the letter primes: The letter itself (e.g., H) is the best-matching letter, better than the target letter (e.g., A) that it substitutes for. Thus, whereas a visually similar digit (4) may be taken as an instance of the target letter it is substituted for (A), a visually similar letter (H) cannot be—the latter would be just as poor an instance of the target letter as would a letter that is visually dissimilar to the target (e.g., D). Consequently, a visually similar digit prime (e.g., 484NDON) can facilitate the retrieval of a lexical representation corresponding to the target word (i.e., produce priming) better than a visually dissimilar digit prime, but a prime containing letter substitutions would produce similar amounts of priming, irrespective of the visual similarity of the substituted letters to the target letters.

This notion of competition that exists between letters may be implemented within an interactive-activation framework (adopted by almost all models of visual word recognition, including DRC (Coltheart et al., 2001), MROM (Grainger & Jacobs, 1996), the spatial-coding model (Davis, 2010), and the various open-bigram models) or a Bayesian framework (the Bayesian Reader model (Norris, 2006), and its successors, the noisy slot model (Norris et al., 2010) and the noisy channel model (Norris & Kinoshita, 2012). In the interactive-activation framework, competition is typically implemented in the form of reciprocal inhibitory connections: For example, the letter representations A and H may be connected by a bidirectional inhibitory link, such that the activation of one drives down the activation of the other. Such within-level mutual inhibition is common in the interactive-activation framework and reflects the assumption that a representation cannot be two different things simultaneously—it is either the letter A or H; it cannot simultaneously be both A and H. Competition between perceptually similar items is also an intrinsic feature within a Bayesian framework. In order to recognize a letter, the reader must accumulate enough evidence to distinguish that letter from a perceptually similar letter. According to Bayes’s theorem, the probability of each letter is a function of the evidence for that letter (called the “likelihood”), divided by the evidence for all of the other letters. Obviously, the greater the evidence for an alternative letter, the more competition there would be.

A question raised by this analysis is why the priming data showed that effectively, no competition took place between the letter A and the digit 4. Just as a representation cannot simultaneously be A and H, it cannot be both A and 4, yet the priming data showed that 4 was taken as an instance of A, but that H was not. This cannot be attributed to the greater physical resemblance between 4 and A than between H and A, because the 2AFC perceptual identification data showed that the visually similar digits were just as difficult to discriminate from the base letter as the visually similar letters.

We suggest that the difference between digits and letter primes observed in the present lexical decision experiment follows naturally from a Bayesian framework, which assumes that what serves as an effective competitor is guided by the task. In the lexical decision task, the goal of the task is to decide whether the letter string is a word, and here, the targets were all strings of letters. This involves accumulating the

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4 Although the present study was not specifically designed to distinguish between these models, the finding of a visual-similarity effect for the digit primes presents a problem for open-bigram models that claim that open bigram representations are specific to letter stimuli (see, e.g., Massol, Duñabeitia, Carreiras, & Grainger, 2013). Such models wrongly predict no difference between the similar- and dissimilar-digit primes (e.g., 484NDON and 676NDON for ABANDON), because they contain the same numbers of letters/open bigrams that overlap with the target.
evidence for the hypothesis “which letter,” not “which letter or digit?” The digit 4 does not serve as a competitor to the letter A because it is written out of contention by the nature of the task (and the targets used): In the lexical decision task, the task-guided expectation is that the input contains only letters, not digits. The visually similar digit 4 contributes almost as much evidence as the letter A for the hypothesis that it is the letter A, because the hypothesis does not consider the possibility that it is a digit. The way that priming is modulated by the nature of the decision rather than simply by the similarity of the form of the stimulus is analogous to the pattern of letter priming reported by Norris and Kinoshita (2008), discussed in the introduction. Using the same different task, they found that the similarity of the prime and the target letter only played a role when the task was to judge whether the referent and the target were physically identical. In that case, the decision about the form of the stimulus must necessarily be influenced by the physical overlap between prime and target. When the task was to judge whether the letters had the same name, the exact form of the stimulus was no longer relevant, and no effect of the similarity of the prime and the target letters emerged. This account also explains why there was no asymmetry in leet priming for digit primes versus letter primes in the same different task (Kinoshita & Lagoutaris, 2010), since in that task both digit and letter reference strings were used.

In closing, we note a parallel in the emerging consensus regarding the role of the so-called “visual word form area” (VWFA). Brain imaging studies have shown that an area in the left fusiform gyrus, along the ventral pathway, supports the perception of abstract orthographic forms (see, e.g., Dehaene & Cohen, 2011; Dehaene et al., 2004), and lesions at or near this region have long been known to result in a relatively specific impairment of fluent reading (“pure alexia”; Dejerine, 1892). However, spirited debate has attended whether this area is selectively or preferentially responsive to letters rather than to other visual objects (e.g., Price & Devlin, 2003; Vogel, Petersen, & Schlaggar, 2012). In this context, it is relevant to note that there is growing recognition that the finding of a “wordlikeness gradient” (i.e., greater hemodynamic activity for more wordlike stimulus) in the VWFA is task-dependent (e.g., Wang, Yang, Shu, & Zevin, 2011) and that the role of this area for reading is not static. Dehaene and Cohen noted that “purely bottom-up visual factors are not the sole determinant of its organization” (p. 260), and A. C. Vogel et al. wrote that “we are arguing that the (putative) VWFA may not be best conceived of as a ‘letter’ or ‘word’ area. Instead, we hypothesize that left OT cortex becomes useful for processing words and letters due to its information processing properties” (p. 2730). Our account of the dynamic nature of the visual similarity of letters and digits is entirely consistent with these views.

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**Appendixes**

**Appendix A**

**Table 2** Stimuli used and the error rates (ER) in the two-alternative forced choice (2AFC) perceptual identification task used to select the letters used as substitutes in the prime

| Target letter | Similar Distractor | ER | Dissimilar Distractor | ER |
|---------------|--------------------|----|-----------------------|----|
| A             | Digit distractor   | 4  | 6                     | 22.2 |
|               | Letter distractors | H  | D                     | 24.6 |
|               |                    | R  | C                     | 30.9 |
| E             | Digit distractor   | 3  | 9                     | 31.7 |
|               | Letter distractors | F  | Q                     | 28.6 |
|               |                    | B  | C                     | 24.6 |
| I             | Digit distractor   | 1  | 2                     | 18.3 |
|               | Letter distractors | L  | G                     | 14.3 |
|               |                    | T  | R                     | 21.4 |
| S             | Digit distractor   | 5  | 7                     | 31.7 |
|               | Letter distractors | E  | D                     | 28.6 |
|               |                    | Z  | I                     | 55.6 |
| B             | Digit distractor   | 8  | 7                     | 29.4 |
|               | Letter distractor  | R  | W                     | 26.9 |
|               |                    | P  | V                     | 33.3 |

In this 2AFC identification task, 21 participants, in addition to the participants in the experiment described in the article, were tested. The procedure was identical to that described in the Method section of the main experiment, except that the prime duration was 53 ms, instead of 40 ms. On the basis of this data, the letter distractors in the first row (e.g., for the target A, the letters H and D) were selected as the letter substitutions to be used in the lexical decision experiment. The letter E was not used in the main experiment.
## Appendix B

**Table 3** List of the critical stimuli used in the lexical decision experiment

| Target  | Identity | Digitsim | Digitdis | Letsim | Letdis | ALD     |
|---------|----------|----------|----------|--------|--------|---------|
| abandon | ABANDON  | 484NDON  | 676NDON  | HHNDON | DWNDON | PRODUCT |
| absence | ABSENCE  | 485ENCE  | 677ENCE  | HREENCE | DWEENCE | VARIETY |
| address | ADDRESSE | 4DDRE55  | 6DDRE77  | HDDREEE | DDDREDD | MORNING |
| anxious | ANXIOUS  | 4NX1O5U | 6NX2O7U | HNXLUEE | DNXGOUD | TRACTOR |
| balance | BALANCE  | 84L4NCE  | 76L6NCE  | RHLHANCE | WDLNCE | POTTERY |
| clarity | CLARITY  | CL4R1TY  | CL6R2TY  | CLHR3TY | CLDRGTY | WESTERN |
| fashion | FASHION  | F45H1ON  | F67H2ON  | FHEHLON  | FDDHGN | CENTURY |
| husband | HUSBAND  | HU584ND  | HU776ND  | HUERHND  | HUDWDND | REFUSAL |
| initial | INITIAL  | 1N1T14L  | 2N2T26L  | 1NNLTLH | GNNTGD | STRANGE |
| justify | JUSTIFY  | JU5T1FY  | JU7T2FY  | JUETLFY  | JUDTGFY | PIONEER |
| massive | MASSIVE  | M4551VE  | M6772VE  | MHEELVE  | MDGVE | SERVANT |
| minimal | MINIMAL  | MIN1M4L  | M2N2M6L  | MLNLMHL  | MGNGMDL | CLIMATE |
| pacific | PACIFIC  | P4C1F1C  | P6C2F2C  | PHLFLEC  | PDCGFGC | JOURNEY |
| plastic | PLASTIC  | PL45T1C  | PL67T2C  | PHLETLC  | PLDPTGC | SOMEHOW |
| success | SUCCESS  | 5UCCE5S  | 7UCCE77  | EUCCEEE  | UCEDD | MOVABLE |
| traffic | TRAFFIC  | TR4FF1C  | TR6FF2C  | TRHFFLC  | TRDFFGC | OPTIMUM |
| usually | USUALLY  | U5U4LLY  | U7U6LLY  | UEUHLHY  | UDDL | CONDUCT |
| utopian | UTOPIAN  | UTOPI14N | UTOPI26N | UTOPLHN  | UTOPGD | MYSTERY |
| visible | VISIBLE  | V1518LE  | V2727LE  | VLELRL | VGGDWLE | NERVOUS |
| worship | WORSHIP  | WOR8H1P  | WOR7H2P  | WOREHL | WOHRGP | BUILDER |
| ability | ABILITY  | 481L1TY  | 672L2TY  | HRLLLTY  | DWG LTY | VOLTAGE |
| caution | CAUTION  | C4UT1ON  | C6UT2ON  | CHTULON  | CDTGON | PROCEED |
| cavalry | CAVALRY  | C4V4LRY  | C6V6LRY  | CHVHLRY  | CDVLR | ACCOUNT |
| curious | CURIOUS  | CUR1OU5  | CUR2OU7  | CURLOUE  | CURGOUD | MEANING |
| dynamic | DYNAMIC  | DYN4M1C  | DYN6M2C  | DYNHML | DYNMD | HELPFUL |
| embassy | EMBASSY  | EM8455Y  | EM7677Y  | EMHRHRY  | EMWD | WELCOME |
| insight | INSIGHT  | 1N51GHT  | 2N72GHT  | LNELGHT  | GNDGHT | TEXTURE |
| instant | INSTANT  | 1N5T4NT  | 2N7T6NT  | LNETHNT  | GNDTNT | FORMULA |
| minimum | MINIMUM  | MIN1M4M  | MIN2M6M  | MLNLMLM  | MGNGMUM | TEXTILE |
| mission | MISSION  | M15510N  | M2772ON  | MLEELO | MGDGON | COTTAGE |
| mustard | MUSTARD  | MJ5T4RD  | M7756RD  | MUETHRD  | MUDRD | WELCOME |
| obvious | OBVIOUS  | O8V1O5U  | O7V2O7U  | ORVLOUE  | ORVGOU | DAYTIME |
| optimal | OPTIMAL  | OPT1M4L  | OPT2MGL  | OPTLMHL  | OPTGMDL | RESPECT |
| painful | PAINFUL  | P41NFUL  | P62NFUL  | PHLNFUL  | PDGNF | BROTHER |
| physics | PHYSICS  | PHY51C5  | PHY727C  | PHYLECE  | PHYDGCD | NETWORK |
| quality | QUALITY  | QU4L1TY  | QU6L2TY  | QUHLLTY  | QULDGT | LITERAL |
| serious | SERIOUS  | 5ER1O5U  | 7ER2O7U  | EERLOUE  | ERGD | HIGHEST |
| similar | SIMILAR  | 51M1L4R  | 72M2L6R  | ELMILH | DGNGLDR | REPLACE |
| station | STATION  | 5T4T1ON  | 77622ON  | ETHTLON  | DTDGN | INVOLVE |
| tourist | TOURIST  | TOUR15T  | TOUR27T  | TOURET | TOURGD | DESTROY |
| arrival | ARRIVAL  | 4RR1V4L  | 6RR2V6L  | HRRVHLH | DRGVDL | DESPITE |
| circuit | CIRCUIT  | C1RC1UT  | C2RCU2T  | C1RCUT  | CRGCUT | QUARREL |
| consist | CONSIST  | CON515T  | CON727T  | CONELET  | CONGDT | STRETCH |
| crucial | CRUCIAL  | CRUC14L  | CRUC26L  | CRUCHL | CRUCGD | SUBJECT |
| darling | DARLING  | D4RL1NG  | D6RL2NG  | DRHLLNG  | DDLRNG | SENATOR |
| dignity | DIGNITY  | D1GIN1TY | D2GN2TY  | DLGNLT | DNGNT | PAYMENT |
| Target     | Identity | Digitsim  | Digitdis | Letsim  | Letdis  | ALD  |
|-----------|----------|-----------|----------|---------|---------|------|
| discuss   | DISCUSS  | D15C055   | D27C077  | DLECEUE | DGDCCDE | COMPLEX |
| disease   | DISEASE  | D15E45E   | D27E67E  | DLEEEHE | DGDDEDE | PROTEIN |
| drawing   | DRAWING  | DR4W1NG   | DR6W2NG  | DRH3WLN | DRHDWNG | INTENSE |
| halfway   | HALFWAY  | H4LFW4Y   | H6LFW6Y  | HLFWHLY | HHDWFHD | JUSTICE |
| highway   | HIGHWAY  | H1GHW4Y   | H2GHW6Y  | HLGHWY  | HGGHWY  | RELEASE |
| instead   | INSTEAD  | 1N5TE4D   | 2N7TE6D  | LNETEHD | GNTEDED | CEILING |
| maximum   | MAXIMUM   | M4X1MUM   | M6X2MUM  | MXLMUM  | MXMGUM  | PICTURE |
| passion   | PASSION   | P4551ON   | P6772ON  | PHEELON | PDDLGDON | DEFENSE |
| reality   | REALITY   | RE4L1TY   | RE6L2TY  | REHLYT  | REDLGTY | STUDENT |
| sponsor   | SPONSOR   | 5PON5OR   | 7PON7OR  | EPONEOR | DPDONDOR | DENSITY |
| stadium   | STADIUM   | 5T4D1UM   | 7T6D2UM  | ETHDLUM  | DTDGDM  | PITCHER |
| surplus   | SURPLUS   | 5URPLU5   | 7URPLU7  | EURPLUE  | DURPLUD | MEETING |
| transit   | TRANSIT   | TR4N5T1R  | TR6N7T2  | TRNELGT  | TRNDGTL | PAYROLL |
| various   | V4R1OUS   | V6R20U7   | VHRLOUE  | VDGROUD | nowhere |
| billion   | BILLION   | 81LL1ON   | 72LL2ON  | RLLLION  | WLLLGON | COURAGE |
| cabinet   | CABINET   | C481NET   | C672NET  | CHRLNET  | CDWGNET | PRIVATE |
| contain   | CONTAIN   | CONT41N   | CONT62N  | CONTHLN  | CONTDGN | FALLOUT |
| crystal   | CRYSTAL   | CRY5T4L   | CRY7T6L  | CRYETHL  | CRYTDTL | INCLUDE |
| finance   | FINANCE   | F1N4NCE   | F2N6NCE  | FLNHNCE  | FNDNCE  | NUCLEAR |
| imagine   | IMAGINE   | I1M4G1NE  | 2M6G2NE  | LMHGGLNE | GMGGLNE | HERSELF |
| inquiry   | INQUIRY   | IN4QUIR   | 2NQU2RY  | LNQLRY   | GNQUGRY | DIVORCE |
| mankind   | MANKIND   | M4K1N1D   | M6N2K2D  | MHNKLND  | MDNKNGND | REVERSE |
| marshal   | MARSHAL   | M4R5H4L   | M6R7H6L  | MHRHHL  | MDRDHL  | HUNDRED |
| million   | MILLION   | M2LL1ON   | M2LL2ON  | MLLLION  | MGLLGON | COMFORT |
| organic   | ORGANIC   | ORG4N1C   | ORG6N2C  | ORGHNLNC | ORGDNGC | GENUINE |
| passage   | PASSAGE   | P4554GE   | P6776GE  | PHEEHEG | PDDGDGE | SHERIFF |
| session   | SESSION   | 5E551ON   | 7E772ON  | EEELON   | DEDGON  | TROUBLE |
| sizable   | SIZABLE   | 51248LE   | 72267LE  | ELZHRL  | DGDWLE  | TEACHER |
| stomach   | STOMACH   | 5TOM4CH   | 7TOM6CH  | ETOHCH   | DTMCH   | VETERAN |
| summary   | SUMMARY   | SUMM4RY   | SUMM6RY  | EUMMHRY  | DUMMHRY | CAREFUL |
| suspect   | SUSPECT   | 5U5PECT   | 7U7PECT  | EUPECT   | DUDPECT | FORTUNE |
| tobacco   | TOBACCO   | TO84CCO   | TO76CCO  | TOHCCO  | TOCDCC  | FATUR |
| unusual   | UNUSUAL   | UNUSU4L   | UNU7U6L  | UNUEUHL  | UNUDULD | MACHINE |
| useless   | USELESS   | U5ELE5S   | U7ELE77  | UEELEE  | UDELEDD | DEVELOP |
| amazing   | AMAZING   | AM4Z1NG   | AM6Z2NG  | HMZLNG  | DMZLGNG | OUTDOOR |
| assault   | ASSAULT   | 4554ULT   | 6776ULT  | HEEHULT  | DDDULT  | SOLDIER |
| classic   | CLASSIC   | CL4551C   | CL6772C  | CLHEELC  | CLDGGDC | TANGENT |
| display   | DISPLAY   | D15PL4Y   | D27PL6Y  | DLEPHLY  | DGDPLDY | REQUIRE |
| exhibit   | EXHIBIT   | EXH181T   | EXH272T  | EXHLRT  | EXHGWGT | OBSCURE |
| fiction   | FICTION   | F1C1TION  | F2C2T2ON | FLCTLON  | FGCTGON | COMPARE |
| finally   | FINALLY   | F1N4LLY   | F2N6LLY  | FNLHLLY | FGDLLLY | PLASTER |
| library   | LIBRARY   | L1B4RY    | L2R6RY   | LLRRRHY  | LGWRDRY | SECULAR |
| musical   | MUSICAL   | MU5IC4L   | MU72C6L  | MUCLCHL  | MUCGCGL | HARMONY |
| natural   | NATURAL   | N4TUR4L   | N6TUR6L  | NHTURHL  | NTURDRL | SURFACE |
| optical   | OPTICAL   | OPT1C4L   | OPT2C6L  | OPTCLCHL | OPTCGDCL | HOSTILE |
| primary   | PRIMARY   | PR1M4RY   | PR2M6RY  | PRMLMRY  | PRGMDRY | YOUNGER |
| pursuit   | PURSUIT   | PUR5UIT   | PUR7U2T  | PURUELT  | PURUGT  | FACULTY |
| radical   | RADICAL   | R4DIC4L   | R6DC26L  | RHDLCGL  | RGDGCDL | IMPULSE |
| realism   | REALISM   | RE4L15M   | RE6L27M  | REHLLEM  | REDLGDM | NOTABLE |
Table 3 (continued)

| Target | Identity | Digitsim | Digitdis | Letsim | Letdis | ALD |
|--------|----------|----------|----------|--------|--------|-----|
| satisfy | SATISFY | 54T15FY | 76T27FY | EHTLEFY | DDTGDFY | GESTURE |
| fellow | FELLOW | 5OF1L5E | 7OF27LE | EFOLLLE | DDFLLDE | FORGIVE |
| typical | TYPICAL | 5YP1C4L | 7YP2C6L | TYLPC4L | TYPGCDL | FORGIVE |
| warrant | WARRANT | 5WR4RNT | 7WR6RNT | WRRHRNT | WDRDNT | THEOREM |
| airport | AIRPORT | 41RPORT | 62RPORT | HLRPORT | DGRPORT | EDITION |
| attract | ATTRACT | 4TTR4CT | 6TR6CT | HTTRHCT | DTRDCT | EMPEROR |
| bathing | BATHING | 84TH1NG | 76TH2NG | RHTH1NG | WTHDGH | LECTURE |
| capable | CAPABLE | 4CP48LE | 6CP67LE | CHFHRLE | CDPWDL | HORIZON |
| capital | CAPITAL | 4CP1T4L | 6CP2T6L | CHP1TLH | CDPFLDL | UNIFORM |
| despair | DESPAIR | 5E5P41R | 7E7P62R | DEEPHLE | DEPPDGR | FREIGHT |
| distant | DISTANT | 5D15T4NT | 7D27T6NT | DLENTNT | DGETNT | CONCERN |
| foolish | FOOLISH | 5FO015H | 7FO027H | FOOLLEH | FOOLGH | SPEAKER |
| furnish | FURNISH | 4FURN1SH | 6FURN27H | FURNLHE | FURNGDH | SCIENCE |
| gradual | GRADUAL | 4GR4DU4L | 6GR6DU6L | GRHDUHL | GRRDUDL | BATTERY |
| holiday | HOLIDAY | 5HOL1D4Y | 7HOL2D6Y | HOLLHLY | HOLLGHD | CHICKEN |
| liberal | LIBERAL | 4LI8ER4L | 6L27ER6L | LWRERHL | LGWERDL | Suppose |
| liberty | LIBERTY | 5LI8ERTY | 7L27ERTY | LERERTY | LGWERTY | COUNTER |
| logical | LOGICAL | 5LOGIC4L | 6LOGIC6L | LOGLCHL | LOGCGL | FIFTEEN |
| message | MESSAGE | 5ME554GE | 7ME776GE | MEHEEHG | MEEEHGE | MEDDGE |
| missile | MISSILE | 5M1551LE | 7M2772LE | MELLLEL | MGDDGLE | ETHICAL |
| mistake | MISTAKE | 5M15T4KE | 7M2776KE | MLETHKE | MGDTKDE | ACADEY |
| opinion | OPINION | 5OP1N1ON | 7OP2N2ON | OPLNLON | OPNGNOM | COLONEL |
| qualify | QUALIFY | 5QU411FY | 7QU6L2FY | QHL1FFY | QUL1FFY | SLENDER |
| vicious | VICEOUS | 5VIC10US | 7VIC20U7 | VCLLOUE | VGC0UD | CONCEPT |

| Target = target word, Identity = identity prime, Digitsim = similar-digit prime, Digitdis = dissimilar-digit prime, Letsim = similar-letter prime, Letdis = dissimilar-letter prime, ALD = all-letter-different control prime |

References

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.

Baayen, R. H. (2011). *LanguageR: Data sets and functions with “Analyzing linguistic data: A practical introduction to statistics.”* (Version 1.4). Retrieved from the CRAN archive: http://cran.r-project.org/src/contrib/Archive/languageR/

Balota, D. A., Cortese, M. J., Hutchison, K. A., Neely, J. H., Nelson, D., Simpson, G. B., & Treiman, R. (2007). The English Lexicon Project: A web-based repository of descriptive and behavioral measures for 40,481 English words and nonwords. Retrieved from http://elexicon.wustl.edu/

Bates, D., Maechler, M., & Bolker, B. (2013). lme4: Linear mixed-effects models using S4 classes [Software] (R package version 0.999999-2). Retrieved from http://cran.r-project.org/package=lme4

Bowers, J. S., Vigliocco, G., & Haan, R. (1998). Orthographic, phonological, and articulatory contributions to masked letter and word priming. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1705–1719. doi:10.1037/0096-1523.24.6.1705

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*, 977–990. doi:10.3758/BRM.41.4.977

Carreiras, M., Dunabeitia, J. A., & Perea, M. (2007). READING WORDS, NUMB3R5 and $YMßOLS. *Trends in Cognitive Sciences, 11*, 454–455. doi:10.3758/BRM.41.4.977

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*, 204–256. doi:10.1037/0033-295X.108.1.204

Carreiras, M., Cortese, M. J., Hutchison, K. A., Neely, J. H., Nelson, D., Simpson, G. B., & Treiman, R. (2007). The English Lexicon Project: A web-based repository of descriptive and behavioral measures for 40,481 English words and nonwords. Retrieved from http://elexicon.wustl.edu/

Bates, D., Maechler, M., & Bolker, B. (2013). lme4: Linear mixed-effects models using S4 classes [Software] (R package version 0.999999-2). Retrieved from http://cran.r-project.org/package=lme4

Bowers, J. S., Vigliocco, G., & Haan, R. (1998). Orthographic, phonological, and articulatory contributions to masked letter and word priming. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1705–1719. doi:10.1037/0096-1523.24.6.1705

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*, 977–990. doi:10.3758/BRM.41.4.977

Carreiras, M., Dunabeitia, J. A., & Perea, M. (2007). READING WORDS, NUMB3R5 and $YMßOLS. *Trends in Cognitive Sciences, 11*, 454–455. doi:10.3758/BRM.41.4.977

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535–555). Hillsdale, NJ: Erlbaum.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*, 204–256. doi:10.1037/0033-295X.108.1.204

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review, 117*, 713–758. doi:10.1037/a0019738

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review, 117*, 713–758. doi:10.1037/a0019738

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences, 15*, 254–262.

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences, 15*, 254–262.

Dejerine, J. (1892). Contribution à l'étude anatomo-pathologique et clinique des différentes variétés de cécité verbale. *Comptes Rendus des Séances et Mémoires de la Société de Biologie, 4*, 61–90.
Forster, K. I., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*, 680–698. doi:10.1037/0278-7393.10.4.680

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology, 39*, 211–251. doi:10.1080/00961528708401785

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35*, 116–124. doi:10.3758/BF03195503

Grainger, J., & Van Heuven, W. J. B. (2004). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *Mental lexicon: Some words to talk about words* (pp. 1–23). Hauppauge, NY: Nova Science.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language, 59*, 434–446. doi:10.1016/j.jml.2007.11.007

Kinoshita, S., & Kaplan, L. (2008). Priming of abstract letter identities in the letter match task. *Quarterly Journal of Experimental Psychology, 61*, 1873–1885. doi:10.1080/17470210701781114

Kinoshita, S., & Lagoutaris, S. (2010). Priming by NUMB3R5 does not involve top-down feedback. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1422–1440. doi:10.1037/a0020609

Kinoshita, S., & Norris, D. (2011). Does the familiarity bias hypothesis explain why there is masked priming for “NO” decisions? *Memory & Cognition, 39*, 319–334. doi:10.3758/s13421-010-0021-8

Kučera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English*. Providence, RI: Brown University Press.

Massol, S., Duñabeitia, J. A., Carreiras, M., & Grainger, J. (2013). Evidence for letter-specific position coding mechanisms. *PLoS ONE, 8*, e68460. doi:10.1371/journal.pone.0068460

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88*, 375–407. doi:10.1037/0033-295X.88.5.375

Mueller, S. T., & Weidemann, C. T. (2012). Alphabetic letter identification: Effects of perceivability, similarity, and bias. *Acta Psychologica, 139*, 19–37. doi:10.1016/j.actpsy.2011.09.014

Norris, D. (2006). The Bayesian Reader: Explaining word recognition as an optimal Bayesian decision process. *Psychological Review, 113*, 327–357. doi:10.1037/0033-295X.113.2.327

Norris, D., & Kinoshita, S. (2008). Perception as evidence accumulation and Bayesian inference: Insights from masked priming. *Journal of Experimental Psychology: General, 137*, 434–455. doi:10.1037/a0012799

Norris, D., & Kinoshita, S. (2012). Reading through a noisy channel: Why there’s nothing special about the perception of orthography. *Psychological Review, 119*, 517–545. doi:10.1037/a0028450

Norris, D., Kinoshita, S., & van Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language, 62*, 254–271. doi:10.1016/j.jml.2009.11.002

Perea, M., Abu Mallouh, R., & Carreiras, M. (2013). Early access to abstract representations in developing readers: Evidence from masked priming. *Developmental Science, 16*, 564–573. doi:10.1111/desc.12052

Perea, M., Duñabeitia, J. A., & Carreiras, M. (2008). R34DING W0RDS WITH NUMB3R5. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 237–241. doi:10.1037/0096-1523.34.1.237

Perea, M., Duñabeitia, J. A., Pollatsek, A., & Carreiras, M. (2009). Does the brain regularize digits and letters to the same extent? *Quarterly Journal of Experimental Psychology, 62*, 1881–1888

Price, C., & Devlin, J. T. (2003). The myth of the visual word form area. *Neuro Image, 19*, 473–481.

R Development Core Team. (2013). *R: A language and environment for statistical computing [Computer software]*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from www.R-project.org

Vogel, A. C., Petersen, S. E., & Schlaggar, B. L. (2012). The left occipitotemporal cortex does not show preferential activity for words. *Cerebral Cortex, 22*, 2715–2732. doi:10.1093/cercor/bhr295

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunction, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 92–114. doi:10.1037/0096-1523.27.1.92

Wang, X., Yang, J., Shu, H., & Zevin, J. D. (2011). Left fusiform BOLD responses are inversely related to word-likeness in a one-back task. *Neuro Image, 53*, 1346–1356.

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review, 8*, 221–243. doi:10.3758/BF03196158

Whitney, C. (2008). Comparison of the SERIOL and SOLAR theories of letter-position encoding. *Brain and Language, 107*, 170–178. doi:10.1016/j.bandl.2007.08.002