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Is there a 'fete' in 'fetish'? Effects of orthographic opacity on morpho-orthographic segmentation in visual word recognition ☆

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Abstract

Recent research using masked priming has suggested that there is a form of morphological decomposition that is based solely on the appearance of morphological complexity and that operates independently of semantic information [Longtin, C.M., Segui, J., & Hallé, P. A. (2003). Morphological priming without morphological relationship. *Language and Cognitive Processes, 18*, 313–334; Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review, 11*, 1090–1098]. The research presented here asks whether this morpho-orthographic segmentation process breaks down for derived stimuli that cannot be segmented perfectly into their morphemic components. Three masked priming experiments are presented that demonstrate that morpho-orthographic segmentation is robust to a series of common orthographic alterations found in complex words, including (a) missing 'e' (e.g., adorable–ADORE), (b) shared 'e' (e.g., lover–LOVE), and (c) duplicated consonant (e.g., dropper–DROP). Our fourth experiment demonstrates that this robustness to orthographic disruption is preserved even in the absence of a semantic relationship between prime and target (e.g., committee–COMMIT; badger–BADGE; fetish–FETE). Results are discussed in terms of the nature of the orthographic representations used in skilled reading.

Keywords: Morphology; Visual word recognition; Reading; Parsing; Masked priming

Introduction

One of the key themes of research on visual word recognition over the past 30 years has concerned the processes through which skilled readers recognize printed words comprising more than one morpheme (e.g., Taft & Forster, 1975). Though a matter of controversy for some years, there now seems to be a fairly broad consensus that morphologically-complex words are somehow 'decomposed' in visual word recognition and analyzed

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in terms of their constituents (e.g., darkness → [dark] + [-ness]). For example, it is widely accepted that the speed with which a morphologically-complex word is recognized is determined in part by the frequency of its stem (e.g., New, Brysbaert, Segui, Ferrand, & Rastle, 2004; Niswander, Pollatsek, & Rayner, 2000). Further, it is also well established that the recognition of a stem target is facilitated by the prior presentation of a morphologically related prime (e.g., Stanners, Neiser, Hernon, & Hall, 1979), in a manner that cannot be explained by simple summed effects of the meaning and letter overlap characteristic of most morphological relatives (Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Research at present is thus turning away from the question of *whether* morphologically-complex words are decomposed, and instead beginning to focus on the question of *how* they are decomposed.

Many researchers interested in morphology have taken the view that morphological decomposition is a high-level phenomenon constrained by semantic knowledge (Marslen-Wilson, Tyler, Waksler, & Older, 1994; see also e.g., Davis, van Casteren, & Marslen-Wilson, 2003; Giraudo & Grainger, 2000; Plaut & Gonnerman, 2000; Rueckl & Raveh, 1999). This perspective on decomposition gained prominence through a series of cross-modal priming experiments in which Marslen-Wilson et al. (1994) demonstrated that the recognition of a stem target (e.g., depart) is facilitated by the prior presentation of a morphologically related prime, but only if that prime is also semantically related to the target (e.g., 'departure' but not 'department' primes 'depart'). These findings led Marslen-Wilson et al. (1994) to claim that words comprising more than one morpheme are decomposed only in cases in which the meaning of the complex word can be derived from the meanings of its constituents (e.g., 'department' would not be decomposed since its meaning cannot be derived from the meanings of [depart] + [-ment]). Further evidence consistent with this 'morpho-semantic' perspective on decomposition has since been reported in a variety of tasks including cross-modal priming (e.g., Longtin, Segui, & Hallé, 2003; Meunier & Longtin, 2007), visual priming with fully visible primes (e.g., Rastle et al., 2000), and unprimed lexical decision (e.g., Ford, Marslen-Wilson, & Davis, 2003).

However, more recent research has challenged the view that decomposition is governed by semantic information. This growing body of literature suggests instead that decomposition is based solely on the existence of a *morphological surface structure* (e.g., any legal stem plus any legal suffix; Gold & Rastle, in press; Lavric, Clapp, & Rastle, 2007; Longtin & Meunier, 2005; Longtin et al., 2003; Rastle & Davis, 2003; Rastle et al., 2000; Rastle, Davis, & New, 2004). Evidence for this 'morpho-orthographic' perspective on decomposition has been obtained in priming experiments in which primes are masked and presented so briefly (e.g., 42 ms) that they are unavailable for conscious report. Under these brief exposure conditions, researchers have observed significant and equivalent priming effects on visual lexical decision for semantically related (e.g., darkness–dark), pseudo-morphological (e.g., corner–corn), and even illegal morphological (e.g., spendical–spend) pairs. Critically, these priming effects are not observed for pairs that bear only a non-morphological form relationship (e.g., brothel–broth; -el never functions as an English affix), indicating that they are not the result of simple letter overlap.

Meunier and Longtin (2007) have recently tried to reconcile these two sets of findings. They started with the observation (Rastle & Davis, 2003) that (a) evidence for morpho-orthographic decomposition (e.g., 'corner' priming 'corn') is seen only under brief exposure conditions thought to reflect the earliest stages of visual word processing; while (b) evidence for morpho-semantic decomposition (e.g., 'corner' not priming 'corn') is limited to tasks thought to reflect central-semantic components of the language system accessed relatively late in processing. From this observation they suggested that the recognition of complex words involves two stages: (a) Decomposition based on morpho-orthographic information; and (b) a licensing procedure during which these morpho-orthographic segmentations are validated for semantic and syntactic legality. Decomposition in their theory is rapid and morpho-orthographic in nature, with incorrect segmentations (e.g., corner → [corn] + [-er]) being rectified at later stages of analysis when semantic/syntactic information becomes available.

The aim of this article is to discover more about morpho-orthographic decomposition. Theoretical accounts of morpho-orthographic decomposition are not yet well developed. However, the preliminary accounts that do exist agree that morphologically-complex stimuli are segmented at the morpheme boundary, in a manner that enables these stimuli to activate the orthographic representations of their stems. It is this pre-activation of the stem representation that accounts for the priming effects on stem recognition that have been observed. For example, one popular notion based on a classical interactive-activation perspective (e.g., Taft, 1994; see also Rastle et al., 2004) is that there is a level of morphemic representation that resides between representations of letters and representations of words, the stem and affix units of which are activated through the explicit morphemic segmentation of stimuli comprising more than one morpheme (e.g., 'corner' activates the stem unit [corn] and the affix unit [-er]). Similarly, distributed-connectionist accounts (e.g., Seidenberg, 1987; see also Rastle et al., 2004) suggest that morphologically-complex words can be represented componentially (i.e., in terms of their morphemic constituents) at the orthographic level as the result of the unique letter probability contours that characterize these stimuli. Bigram and trigram frequencies within morphemes tend to be much higher than those frequencies across morpheme boundaries, thus providing a reliable mechanism for morphemic segmentation in these models in the absence of explicit morphemic representations (see Rastle et al., 2004).

Both of these accounts of morpho-orthographic decomposition are based on the notion that it is possible to segment a morphologically-complex stimulus into its stem and affix components using orthographic information. However, perfect segmentation of this nature is possible for only around 61% of morphologically-complex English words (Baayen, Piepenbrock, & van Rijn, 1993). The remaining 39% of derived English words comprise some type of orthographic alteration that does not allow a perfect parse of the letter string into complete morphemic units. The vast majority of these orthographic alterations are fairly modest rule-based changes (e.g., removing the suffix -able from 'adorable' leaves the non-stem 'ador' instead of the stem 'adore') but more extreme idiosyncratic changes do also occur (e.g., removing the suffix -ant from 'abundant' leaves the non-stem 'abund' instead of the actual stem 'abound'). Our own experiments on morpho-orthographic segmentation (e.g., Rastle & Davis, 2003; Rastle et al., 2000, 2004) have never considered priming effects yielded by stimuli of this nature. Further, though the related experiments in French (Longtin & Meunier, 2005; Longtin et al., 2003) have sometimes included morphologically-structured primes that cannot be parsed perfectly into their morphemic constituents (e.g., 'savonnette' → [savon] + [-ette]), never have priming effects yielded by these stimuli been compared to the priming effects yielded by stimuli that can be parsed perfectly into their constituents (e.g., 'rondelle' → [rond] + [-elle]). Thus, it remains to be seen whether morpho-orthographic segmentation breaks down in the face of the orthographic alterations found in complex words or whether it is robust to them.

The problem of orthographic opacity has recently been investigated in the non-concatenative morphological system of Hebrew by measuring masked morphological priming effects in "weak root" constructions in which one consonant is removed in certain conjugations (Frost, Deutsch, & Forster, 2000). One example of a weak root stimulus is 'hipil' (meaning 'he overthrew'), comprising the word pattern [hi.i.] and the root morpheme [n.p.l]. However, unlike 90% of Hebrew words in which the whole root is present, in this conjugation the first component of the root [n] is missing. Frost et al.'s (2000) basic finding was that the robust masked priming effects normally observed for primes and targets sharing word patterns *vanish completely* when prime stimuli consist of these weak roots. Frost et al. (2000) argued that the Hebrew morphological parsing system must identify two potential morphological structures (a root morpheme and a word pattern) for decomposition, and if any of these two structures is corrupted then the parser will fail.

Though it is possible that English morphological segmentation also breaks down in cases in which part of the stem is missing (e.g., adorable), there are good reasons to believe that it would be more robust than this. One important difference between the Hebrew and English morphological systems concerns the predictability of the orthographic changes that occur in morphologically-complex forms. Though up to 10% of Hebrew conjugations involve weak roots, there is no consistency across conjugations in the particular consonant that is deleted. In contrast, the vast majority of orthographic alterations that occur in English complex words are so predictable that they can be used productively (e.g., 'e' deletion; someone who 'baves' would be a 'bavist' not a 'baveist'). It would be somewhat surprising if English morphological segmentation were not robust to these highly-predictable changes, and would mean that particular stems could be accessed from only *some* of their complex family members (e.g., the stem 'excite' could be accessed from 'excitement' but not from 'excitable' or 'exciting'). But how might this robustness be achieved?

One possible mechanism has been suggested in the literature on spoken word recognition. Many spoken words can occur in a phonologically-altered form (for example, place assimilation alters the pronunciation of the word 'lean' to /lim/ in the sequence 'lean bacon' or to /liŋ/ in the sequence 'lean gammon'). Some researchers have therefore proposed that such words can be represented in an "underspecified" manner in which not all of their phonemic features are stored (Lahiri & Marslen-Wilson, 1991; see also Eulitz & Lahiri, 2004; Gaskell, Hare, & Marslen-Wilson, 1995). This proposal suggests that it is possible to recognize tokens such as /lim/ and /liŋ/ as instances of the word 'lean' in phonological contexts that permit place assimilation because place of articulation information about word-final coronal segments in such words is not specified in the phonological lexicon. Similar arguments have been applied regarding the phonological representations of stems that undergo allomorphic changes in certain derivational contexts (e.g., see Marslen-Wilson & Zhou, 1999; Reid & Marslen-Wilson, 2003). For example, the finding that equivalent delayed auditory priming is observed for morphological pairs with (vanity–vain) and without (maturity–mature) phonological alterations has been interpreted as suggesting that the stem 'vain' is represented in a manner that does not specify those phonetic features of the vowel that change in certain derivational contexts (Marslen-Wilson & Zhou, 1999).

By analogy to visual word recognition, we might therefore propose that the orthographic representations of English stems are underspecified with respect to those aspects of the input that change in certain morphological contexts. For example, stems such as 'adore' or 'love' may be represented orthographically with an underspecified final 'e', thus allowing the rapid activation of the stem representation for derived words in which the final 'e' is omitted (e.g., 'adorable', 'lovable'). There is already some evidence that this might be the case. Taft (1979) compared lexical decision latencies for non-word stimuli like STON (which would be a word if a final 'e' were added) with those for non-word stimuli like SLON (which would not be a word even if a final 'e' were added). He found that the STON non-words were rejected more slowly than the SLON non-words, an interference effect he attributed to the orthographic underspecification of words with silent final 'e' (i.e., stimuli like STONE are stored as STON). Taft (1986) also showed that no analogous interference effect is observed when a final *consonant* is removed from a monosyllabic word (e.g., the nonword BLEN derived from 'blend' is rejected no more slowly than a nonword like GURF that has not been derived from any monosyllabic word), demonstrating that the interference effects observed for STON-type stimuli reflect something special about final silent 'e'. Interestingly, Taft (1979) recognized that suffixation often involves the deletion of a silent final 'e', and claimed that underspecification of 'e'-ending stems would permit stimuli like 'stoning' and 'stone' or 'wisdom' and 'wise' to share orthographic lexical representations. Though no evidence was presented to test this claim, it would predict that masked priming effects should emerge for pairs like adorable–ADORE, even despite the orthographic opacity of the prime stimulus.

Four experiments were therefore conducted to examine the influence of orthographic opacity on morpho-orthographic segmentation. These experiments followed previous research in the field (e.g., Longtin et al., 2003; Rastle & Davis, 2003; Rastle et al., 2004) in comparing masked priming effects yielded by a morphologically-complex stimulus on the recognition of a stem target. The first three of these experiments compared priming effects yielded by orthographically transparent masked morphological primes (e.g., darkness–DARK), orthographically opaque masked morphological primes (e.g., adorable–ADORE), and non-morphological form primes (e.g., brothel–BROTH). These three experiments examined three different types of predictable orthographic alteration found in morphologically-complex English words. The first experiment dealt with the scenario explored by Taft (1979): A missing 'e' at the morpheme boundary (e.g., adorable–ADORE). The second and third experiments then moved on to a shared 'e' at the morpheme boundary (e.g., lover–LOVE, Experiment 2) and a duplicated consonant at the morpheme boundary (e.g., wrapper–WRAP, Experiment 3). Our fourth experiment sought to discover whether our observations would hold for morphologically-structured primes that are orthographically and semantically opaque (e.g., fetish–FETE).

Experiment 1: Missing 'e'

Experiment 1 investigated whether morpho-orthographic segmentation is observed for morphologically-complex words that are orthographically opaque because of a missing 'e' at the morpheme boundary (e.g., adorable). Based on Taft's (1979) findings we would expect priming effects elicited by these words to be comparable to those elicited by morphologically-complex stimuli that can be parsed perfectly into morphemes (e.g., doubtful).

Methods

Participants

The participants were 46 volunteers from Royal Holloway, University of London. Participants had normal or corrected to normal vision and were native speakers of English. Participants were offered £5.00 (about $9) in exchange for their time. No participant in any of our experiments took part in more than one study.

Stimuli

Two hundred prime–target pairs were selected from the CELEX English database (Baayen et al., 1993), fifty in each of four conditions. Each prime in the *transparent morphological* condition was morphologically and semantically related to its respective target, and could be parsed perfectly into the target and a legal suffix (e.g., darkness). Each prime in the *transparent form* condition had an orthographic relationship but no morphological or semantic relationship to its target. Primes in this condition generally comprised the target and a non-morphological ending (e.g., brothel), although in rare cases suffixes that occur only very infrequently across the set of English words were accepted as non-morphological (see also Rastle et al., 2004; e.g., '-o' was accepted as non-morphological because it occurs as a suffix in only three words, 'weirdo', 'doggo', and 'yobbo'). Each prime in the *opaque morphological* condition was morphologically and semantically related to its respective target, but could not be parsed perfectly into the target and a legal suffix because of a missing 'e' at the morpheme boundary (e.g., the prime 'forgivable' cannot be parsed perfectly into the target 'forgive' and the suffix '-able'). Each prime in the *opaque form* condition had a partial orthographic relationship but no semantic or morphological relationship to its target. Primes in this condition contained all but the final letter of their targets plus a non-morphological ending (e.g., the stimulus 'travesty' served as an opaque form prime for the target 'travel').

Stimuli in the two morphological conditions were matched on a variety of factors to stimuli in their respective form control conditions using the Match program (van Casteren & Davis, in press). These factors included target frequency, prime frequency, prime length, target neighborhood, target length, and form overlap (expressed as 'number of target letters/number of prime letters'). Each target had a maximum neighborhood size of 4. Semantic relatedness values for each prime–target pair were obtained using the LSA web facility (Landauer & Dumais, 1997). Pairs in the transparent and opaque morphological conditions were highly semantically related, in contrast to pairs in the non-morphological form conditions. Mean values for each of these variables along with statistical test data are shown in Table 1. Stimuli for this experiment are presented in Appendix A.

Unrelated control primes were selected for each of the target words. Control primes in all of our experiments were morphologically, semantically, and orthographically unrelated to their respective targets. They were matched pairwise on length and morphological complexity to each related prime, and were matched groupwise on frequency to the set of related primes.

Sixty-six pairs of totally unrelated primes and targets were added to the stimulus set in order to reduce the overall relatedness proportion to 37%. Filler targets in all of our experiments were matched groupwise to the experimental targets on frequency, length, and neighborhood size. Filler primes in all of our experiments were matched groupwise to the experimental primes on frequency and length. Half of the primes in each set of filler prime–targets pairs were morphologically complex and half were morphologically simple.

Two hundred and sixty-six 'morphologically simple' non-word targets were selected for the NO response of the lexical decision task. Non-word targets in all of our experiments were matched groupwise to the experimental and filler targets on length and neighborhood size. Non-word targets were always preceded by unrelated word primes, half of which were morphologically complex and half of which were morphologically simple. These primes were matched groupwise to the other primes on length and on frequency.

Targets from each condition were divided at random into two equal lists for counterbalancing purposes, with half of the targets in each list preceded by related primes and half by unrelated control primes. Participants received only one experimental list and therefore participated in all priming conditions, but saw each target word only once. Including the experimental, filler, and non-word trials, each participant made five hundred and thirty-two lexical decisions in this experiment.

Apparatus and procedure

Stimulus presentation and data recording were controlled by the DMDX software (Forster & Forster,

Table 1
Stimulus characteristics for primes and targets across the three conditions in Experiment 1 (Missing 'e')

	Transparent morphological	Transparent form	ANOVA	Opaque morphological	Opaque form	ANOVA
Target frequency	27.90	27.35	$F(1,99) = .00$, n.s.	35.80	37.25	$F(1,99) = 0.02$, n.s.
Prime frequency	4.33	5.73	$F(1,99) = 0.56$, n.s.	11.51	10.66	$F(1,99) = 0.032$, n.s.
Target neighborhood	1.84	1.82	$F(1,99) = 0.01$, n.s.	1.30	1.36	$F(1,99) = 0.045$, n.s.
Prime length	7.36	7.34	$F(1,99) = 0.00$, n.s.	7.50	7.46	$F(1,99) = 0.04$, n.s.
Target length	4.94	4.88	$F(1,99) = 0.11$, n.s.	5.40	5.34	$F(1,99) = 0.15$, n.s.
Form overlap	0.68	0.68	$F(1,99) = 0.03$, n.s.	0.59	0.59	$F(1,99) = 0.01$, n.s.
Semantic relatedness	0.35	0.06	$F(1,90) = 50.53$, $p < .05$	0.34	0.06	$F(1,95) = 48.52$, $p < .05$

Note. Frequency values are per million.

2003) running on a Pentium III personal computer. A two-button response box was used to record lexical decisions, in which the YES response button was controlled by the dominant hand.

Participants were tested in a dimly-lit, quiet room. They were advised that they would be seeing a series of letter strings presented one at a time, and that they would be required to decide as quickly and accurately as possible whether each string was a word or not a word. Participants were not told of the existence of the prime stimulus. Primes were presented in lower case for 42 ms. These primes were preceded by a 500 ms forward mask (consisting of hash marks) and were followed immediately by a target in uppercase that remained on screen until a response was made or until 6 s had elapsed. Targets were presented in a different random order for each participant. Participants were given ten practice trials before beginning the experiment.

Results

RT and error data were cleaned to remove outlying participants, items, and individual data points. Participants in all experiments were excluded if they had an average non-word RT over 1500 ms or a non-word false positive rate over 30%, or if they had an average target RT over 1200 ms or a target error rate over 30%. These criteria led to the exclusion of one participant in this experiment. No items were excluded but a further 66 outlying data points over 1700 ms were removed. The remaining data were subjected to an inverse transformation before analysis in order to reduce the influence of any remaining outliers (Ulrich & Miller, 1994). Means in the text and tables are retransformed as harmonic means, however, in order to show differences between experimental conditions clearly.

Data were analyzed both by subjects and by items using four-factor ANOVAs. The analysis by subjects treated priming (two levels), morphology (two levels) and orthographic opacity (two levels) as repeated factors and list (two levels) as an unrepeated factor. The analysis by items treated morphology, orthographic opacity and list as unrepeated factors and priming as a repeated factor. Interactions between condition and priming in all of our experiments were investigated further through (a) simple comparisons of priming in each condition; and (b) comparisons of priming across conditions. Because our hypotheses concerning priming effects across conditions were all directional, these latter comparisons were conducted with one-tailed tests. Latency and error data for this experiment are shown in Table 2.

The ANOVAs revealed an interaction between morphology and priming [$F_1(1,43) = 18.92$, $p < .05$; $F_2(1,192) = 16.98$, $p < .05$; $\min F'(1,150) = 8.95$, $p < .05$]. In order to investigate the source of this interaction, *t*-tests were used to establish the amount of priming in each condition. There was significant priming in the transparent morphological condition [$t_1(44) = 4.88$, $p < .05$; $t_2(49) = 5.28$, $p < .05$] and only marginally significant form priming in the transparent form condition [$t_1(44) = 1.95$, $p < .10$; $t_2(49) = 1.95$, $p < .10$]. Similarly, there was significant priming in the opaque morphological condition [$t_1(44) = 6.63$, $p < .05$; $t_2(49) = 6.19$, $p < .05$] but no priming in the opaque form condition [$t_1 < 1$; $t_2 < 1$]. These figures were backed up by analyses that compared priming effects in the two morphological conditions with priming effects in the two form conditions. Priming effects in the transparent morphological condition were larger than those in the transparent form condition [$t_1(44) = 1.74$, $p < .05$; $t_2(98) = 2.01$, $p < .05$], and priming effects in the opaque morphological condition were larger than those in the opaque form condition [$t_1(44) = 3.72$, $p < .05$; $t_2(98) = 3.80$, $p < .05$].

Four-factor ANOVAs on the percentage of errors revealed a significant main effect of priming [$F_1(1,43) = 28.61$, $p < .05$; $F_2(1,192) = 22.50$, $p < .05$, $\min F'(1,163) = 12.59$, $p < .05$], as fewer errors were made in the primed conditions than in the control conditions. No other effects in the error data reached significance both by subjects and by items, so these data are not considered further.

Table 2
Latency and error data (by subjects) for Experiment 1 (Missing ‘e’)

Condition	Trans. morph. (darkness–DARK)	Trans. form (brothel–BROTH)
Related primed	584 (3.2%)	619 (10.7%)
Control primed	609 (6.8%)	633 (13.5%)
Priming effect	25 (3.6%) (95% C.I. = ±10 ms)	14 (2.8%) (95% C.I. = ±13 ms)
	Opaque morph. (adorable–ADORE)	Opaque form (optimum–OPTIC)
Related primed	584 (4.5%)	611 (5.5%)
Control primed	612 (7.1%)	611 (7.3%)
Priming effect	28 (2.6%) (95% C.I. = ±9 ms)	0 (1.8%) (95% C.I. = ±14 ms)

Note. Trans. = transparent; morph. = morphological.

Experiment 2: Shared 'e'

Experiment 1 provided evidence that morphologically-complex words that are orthographically opaque because of a missing 'e' at the morpheme boundary (e.g., adorable) undergo a segmentation process that enables them to prime their stems. Experiment 2 investigated whether morpho-orthographic segmentation is robust to a second type of regular orthographic alteration—a shared 'e' at the morpheme boundary (e.g., lover).

Methods

Participants

The participants were 58 volunteers from the same population as was used in Experiment 1.

Stimuli

Ninety prime–target pairs were selected from the CELEX English database (Baayen et al., 1993), thirty in each of three conditions. Each prime in the *orthographically transparent* condition was morphologically and semantically related to its respective target, and could be parsed perfectly into the target and a legal suffix (e.g., darkness). Each prime in the *orthographically opaque* condition was morphologically and semantically related to its respective target, but could not be parsed perfectly into the target and a legal suffix because of a shared 'e' at the morpheme boundary (e.g., the prime 'lover' cannot be parsed perfectly into the target 'love' and the suffix '-er'). Finally, each prime in the *non-morphological form* condition had an orthographic, but not morphological or semantic, relationship with its respective target (e.g., brothel). Primes and targets across the three conditions were matched on the same variables as in Experiment 1. Mean values for each of these variables along with statistical test data are shown in Table 3. Unrelated control primes were selected for each of the 90 target words, using the same criteria as were applied in Experiment 1. Test stimuli for this experiment are presented in Appendix B.

Thirty pairs of totally unrelated primes and targets were added to the stimulus set in order to reduce the overall relatedness proportion to 37%. Further, one hundred and twenty 'morphologically simple' non-word targets preceded by unrelated word primes were selected for the NO response of the lexical decision task. These items were all selected using the same criteria as were applied in Experiment 1.

The administration of prime–target pairs was counterbalanced across participants as in Experiment 1. Each participant made 240 lexical decisions in this experiment.

Apparatus and procedure

The apparatus and procedural details of this experiment were identical to those in Experiment 1.

Results

RT and error data were cleaned as in Experiment 1. Though no participants were removed, three morphologically-structured items had been inadvertently included in the non-morphological form condition (emergent, democratic, and crampon) and were removed. Further, forty-nine outlying data points over 1700 ms were excluded. Data were treated to an inverse transformation, as described in Experiment 1.

Data were analyzed both by subjects and by items using three-factor ANOVAs. The analysis by subjects treated priming (two levels) and condition (three levels) as repeated factors and list (two levels) as an unrepeated factor. The analysis by items treated condition and list as unrepeated factors and priming as a repeated factor. Latency and error data for Experiment 2 are shown in Table 4.

The ANOVAs revealed an interaction between condition and priming that was significant by subjects and marginal by items [$F_1(2,112) = 4.03$, $p < .05$; $F_2(2,81) = 2.42$, $p < .10$; $\min F'(2,165) = 1.51$, $p = .22$]. In order to investigate the source of this interaction, *t*-tests were used to establish the amount of priming within each condition. There was robust priming in the

Table 3
Stimulus characteristics for primes and targets across the three conditions in Experiment 2 (Shared 'e')

	Orthographically transparent	Orthographically opaque	Non-morphological form	ANOVA
Target frequency	52.91	62.93	49.05	$F(2,89) = 0.19$, n.s.
Prime frequency	7.88	6.62	8.62	$F(2,89) = 0.16$, n.s.
Target neighborhood	1.80	1.90	1.73	$F(2,89) = 0.10$, n.s.
Prime length	6.63	6.73	6.63	$F(2,89) = 0.06$, n.s.
Target length	5.17	5.33	5.03	$F(2,89) = 0.80$, n.s.
Form overlap	0.78	0.79	0.77	$F(2,89) = 0.87$, n.s.
Semantic relatedness	0.32	0.33	0.09	$F(2,82) = 11.87$, $p < .05$

Note. Frequency values are per million.

Table 4
Latency and error data (by subjects) for Experiment 2 (Shared 'e')

Condition	Orth. trans. (darkness–DARK)	Orth. opaque (writer–WRITE)	Form (shovel–SHOVE)
Related primed	562 (3.1%)	568 (2.3%)	621 (9.3%)
Control primed	591 (4.3%)	600 (3.8%)	636 (11.2%)
Priming effect	27 (1.2%) (95% C.I. = ±10 ms)	32 (1.5%) (95% C.I. = ±13 ms)	15 (1.9%) (95% C.I. = ±11 ms)

Note. Orth. = orthographically; trans. = transparent.

orthographically transparent condition [$t_1(57) = 6.00$, $p < .05$; $t_2(28) = 3.40$, $p < .05$] and in the orthographically opaque condition [$t_1(57) = 5.01$, $p < .05$; $t_2(28) = 3.65$, $p < .05$], but not in the non-morphological form condition, [$t_1(57) = 2.43$, $p < .05$; $t_2(28) = 1.68$, n.s.]. Further, priming effects in the orthographically transparent condition did not differ from those in the orthographically opaque condition [$t_1 < 1$; $t_2 < 1$]. Conversely, priming effects in the non-morphological form condition were marginally smaller than those in the orthographically transparent condition [$t_1(57) = 2.24$, $p < .05$; $t_2(56) = 1.39$, $p < .10$] and were significantly smaller than those in the orthographically opaque condition [$t_1(57) = 2.15$, $p < .05$; $t_2(56) = 1.63$, $p < .05$].

The ANOVA on the percentage of errors made across each condition revealed a significant effect of priming [$F_1(1, 56) = 7.84$, $p < .05$; $F_2(1, 81) = 4.34$, $p < .05$; min$F'(1, 135) = 2.81$, $p < .10$], with fewer errors being made in the primed conditions than in the control conditions. However, there was no interaction between priming and condition [$F_1 < 1$; $F_2 < 1$]. No other effects on the error data reached significance both by subjects and by items, and so these data were not considered any further.

Experiment 3: Duplicated Consonant

Experiments 1 and 2 provided evidence that morpho-orthographic segmentation is robust to two types of orthographic alteration ('e' deletion and shared 'e'). Experiment 3 investigated whether morpho-orthographic segmentation is robust to a third type of orthographic alteration—a duplicated consonant at the morpheme boundary (e.g., metallic).

Methods

Participants

The participants were 59 volunteers from the same population as was used in Experiment 1.

Stimuli

Ninety prime–target pairs were selected from the CELEX English database (Baayen et al., 1993), thirty in each of three conditions. Each prime in the *orthographically transparent* condition was morphologically and semantically related to its respective stem target, and could be parsed perfectly into the stem target and a legal suffix (e.g., darkness). Each prime in the *orthographically opaque* condition was morphologically and semantically related to its respective target, but could not be parsed perfectly into the target and a legal suffix because of a duplicated consonant at the morpheme boundary (e.g., the prime 'metallic' cannot be parsed perfectly into the target 'metal' and the suffix '-ic'). Finally, each prime in the *non-morphological form* condition had an orthographic, but not morphological or semantic, relationship with its respective target (e.g., brothel). Primes and targets across the three conditions were matched as closely as possible on the same variables as were controlled in Experiment 1. Mean values for each of these variables along with statistical test data are shown in Table 5. Unrelated control primes were selected for each of the 90 target words using the same criteria as were applied in Experiment 1. Stimuli for this experiment are presented in Appendix C.

Thirty pairs of totally unrelated primes and targets were added to the stimulus set in order to reduce the overall relatedness proportion to 37%. Further, one hundred and twenty 'morphologically simple' non-word targets preceded by unrelated word primes were selected for the NO response of the lexical decision task. These items were all selected using the same criteria as were applied in Experiment 1.

Counterbalancing was implemented as in Experiment 1. Each participant made 240 lexical decisions in this experiment.

Apparatus and procedure

The apparatus and procedural details of this experiment were identical to those in Experiment 1.

Results

RT and error data were cleaned as in Experiment 1. Four participants were excluded because of average non-word RTs exceeding 1500 ms. Further, fifty-one outlying data points over 1700 ms were removed.

Data were analyzed both by subjects and by items using three-factor ANOVAs designed in the same man-

Table 5
Stimulus characteristics for primes and targets across the three conditions in Experiment 3 (Duplicated Consonant)

	Orthographically transparent	Orthographically opaque	Non-morphological form	ANOVA
Target frequency	46.85	69.51	55.81	$F(2,89) = 0.45$, n.s.
Prime frequency	6.21	4.59	6.62	$F(2,89) = 0.67$, n.s.
Target neighborhood	1.73	1.80	1.80	$F(2,89) = 0.02$, n.s.
Prime length	8.40	8.53	8.37	$F(2,89) = 0.16$, n.s.
Target length	5.10	5.10	5.17	$F(2,89) = 0.06$, n.s.
Form overlap	0.61	0.60	0.63	$F(2,89) = 1.17$, n.s.
Semantic relatedness	0.38	0.33	0.06	$F(2,82) = 27.72$, $p < .05$

Note. Frequency values are per million.

Table 6
Latency and error data (by subjects) for Experiment 3 (Duplicated Consonant)

Condition	Orth. trans. (darkness–DARK)	Orth. opaque (metallic–METAL)	Form (brothel–BROTH)
Related primed	575 (2.8%)	586 (4.1%)	612 (7.5%)
Control primed	599 (4.0%)	616 (6.4%)	620 (8.7%)
Priming effect	24 (2.8%) (95% C.I. = ±12 ms)	30 (2.1%) (95% C.I. = ±10 ms)	8 (1.2%) (95% C.I. = ±13 ms)

Note. Orth. = orthographically; trans. = transparent.

ner as in Experiment 2. Latency and error data for Experiment 3 are shown in Table 6.

The ANOVAs revealed an interaction between condition and priming [$F_1(2,106) = 4.55$, $p < .05$; $F_2(2,84) = 4.71$, $p < .05$; min$F'(2,188) = 2.31$, $p = .10$]. In order to investigate the source of this interaction, t-tests were used to establish the amount of priming within each condition. There was significant priming in the orthographically transparent condition [$t_1(54) = 4.36$, $p < .05$; $t_2(29) = 4.76$, $p < .05$] and in the orthographically opaque condition [$t_1(54) = 5.72$, $p < .05$; $t_2(29) = 5.37$, $p < .05$], but not in the non-morphological form condition [$t_1(54) = 1.24$, n.s.; $t_2(29) = 1.15$, n.s.]. These figures were backed up by analyses that compared priming effects across conditions. Priming effects in the orthographically transparent condition did not differ from those in the orthographically opaque condition [$t_1 < 1$; $t_2 < 1$]. Conversely, priming effects in the non-morphological form condition were significantly smaller than those in both the orthographically transparent condition [$t_1(54) = 1.87$, $p < .05$; $t_2(58) = 2.15$, $p < .05$] and the orthographically opaque condition [$t_1(54) = 2.45$, $p < .05$; $t_2(58) = 2.83$, $p < .05$].

The ANOVAs on the percentage of errors made across each condition revealed a significant effect of priming [$F_1(1,53) = 7.09$, $p < .05$; $F_2(1,84) = 7.71$, $p < .05$; min$F'(1,127) = 3.69$, $p < .05$], with fewer errors being made in the primed conditions than in the control conditions. However, there was no interaction between priming and condition [$F_1 < 1$; $F_2 < 1$]. No other effects on the error data reached significance both by subjects and by items, and so these data were not considered any further.

Experiment 4: Semantic Opacity

The pattern of results observed in Experiments 1 through 3 is unambiguous. Priming effects induced by morphologically-complex stimuli characterized by one of three regular orthographic alterations (including a duplicated consonant at the morpheme boundary, a shared ‘e’ at the morpheme boundary, or a missing ‘e’ at the morpheme boundary) are equivalent in magnitude to those induced by morphologically-complex stimuli that can be parsed perfectly into their morphemic constituents. Further, all of these morphological priming effects are significantly larger than non-morphological form priming effects. These data appear to indicate that morpho-orthographic segmentation is a flexible process that is robust to the orthographic alterations found in many complex words.

Experiments 1 through 3 all examined the effect of orthographic opacity on morphological decomposition using semantically transparent primes. However, previous research has demonstrated that morpho-orthographic segmentation is also applied to morphologically-structured words that are not semantically related to their stems (e.g., corner; Longtin et al., 2003; Rastle et al., 2004). It is therefore important to determine whether these pseudo-morphological stimuli (e.g., corner) show the same robustness to orthographic alterations as was revealed for the semantically transparent stimuli tested in Experiments 1 through 3. Experiment 4 meets this objective by comparing priming effects elicited by (a) orthographically opaque but semantically transparent stimuli (e.g., lover); (b) orthographically and semantically opaque stimuli (e.g., badger); and (c) non-morphological form controls (e.g., shovel). Due to a shortage of words in the English language that are both orthographically and semantically opaque, the materials for this experiment combine all three forms of orthographic change explored in Experiments 1–3.

Methods

Participants

The participants were 82 volunteers from the same population as was used in Experiment 1.

Stimuli

Ninety prime–target pairs were selected from the CELEX English database (Baayen et al., 1993), thirty in each of three conditions. Each prime in the *semantically related morphological* condition was semantically and morphologically related to its stem target, and contained one of the three orthographic alterations investigated in the previous experiments including consonant duplication (e.g., metallic–METAL), shared 'e' (e.g., lover–LOVE), and missing 'e' (e.g., adorable–ADORE). Each prime in the *semantically-unrelated morphological* condition had a morphological structure, but no semantic relationship to its stem target. Primes in this condition also contained one of the three orthographic alterations investigated in the previous experiments including consonant duplication (e.g., committee–COMMIT), shared 'e' (e.g., badger–BADGE), and missing 'e' (e.g., palatial–PALATE). The number of items containing each type of orthographic alteration was matched across these two morphological conditions (consonant duplication: 2 items; shared 'e': 8 items; missing 'e': 20 items). Each prime in the *non-morphological form* condition had an orthographic relationship, but no semantic or morphological relationship with its respective stem target. Following the design of the morphological primes, ten of the non-morphological form primes contained the entire embedded stem target (e.g., brothel–BROTH) while twenty contained the embedded stem target minus the final letter (e.g., straight–STRAIN).

Primes and targets across the three conditions were matched as closely as possible on the same variables as were controlled in Experiment 1. Mean values for each of these variables along with statistical test data are shown in Table 7. Unrelated control primes were selected for each of the 90 target words, using the same criteria as were applied in Experiment 1. Stimuli for this experiment are presented in Appendix D.

Thirty pairs of totally unrelated primes and targets were added to the stimulus set in order to reduce the overall relatedness proportion to 37%. Further, one hundred and twenty 'morphologically simple' non-word targets preceded by unrelated word primes were selected for the NO response of the lexical decision task. These items were all selected using the same criteria as were applied in Experiment 1.

The administration of prime–target pairs was counterbalanced across participants as in Experiment 1. Each participant made 240 lexical decisions in this experiment.

Apparatus and procedure

The apparatus and procedural details of this experiment were identical to those in Experiment 1.

Results

RT and error data were cleaned as in Experiment 1. Two participants were excluded because of average nonword error rate exceeding 30%, and a further 124 outlying data points over 1700 ms were removed.

Data were analyzed both by subjects and by items using three-factor ANOVAs. The analysis by subjects treated priming (two levels) and condition (three levels) as repeated factors and list (two levels) as an unrepeated factor. The analysis by items treated condition and list as unrepeated factors and priming as a repeated factor. Latency and error data by subjects are shown in Table 8.

The ANOVAs revealed an interaction between condition and priming [$F_1(2,156) = 3.76$, $p < .05$; $F_2(2,84) = 3.34$, $p < .05$; $\min F'(2,210) = 1.77$, $p = .17$]. In order to investigate the source of this interaction, planned com-

Table 7
Stimulus characteristics for primes and targets across the three conditions in Experiment 4 (Semantic Opacity)

	Semantically related morphological	Semantically unrelated morphological	Non-morphological form	ANOVA
Target frequency	37.66	34.19	34.80	$F(2,89) = 0.04$, n.s.
Prime frequency	10.70	10.66	11.40	$F(2,89) = 0.01$, n.s.
Target neighborhood	1.50	1.66	1.53	$F(2,89) = 0.11$, n.s.
Prime length	7.87	7.57	7.33	$F(2,89) = 1.23$, n.s.
Target length	5.93	5.70	5.53	$F(2,89) = 1.13$, n.s.
Form overlap	0.67	0.67	0.67	$F(2,89) = 0.02$, n.s.
Semantic relatedness	0.55	0.06	0.08	$F(2,82) = 11.59$, $p < .05$

Note. Frequency values are per million.

Table 8
Latency and error data (by subjects) for Experiment 4 (Semantic Opacity)

Condition	Sem. related (writer–WRITE)	Sem. unrelated (badger–BADGE)	Form (shovel–SHOVE)
Related primed	597 (2.4%)	618 (6.8%)	620 (5.8%)
Control primed	617 (3.7%)	636 (8.3%)	623 (6.8%)
Priming effect	18 (1.3%) (95% C.I. = ±11 ms)	20 (1.5%) (95% C.I. = ±10 ms)	3 (1.0%) (95% C.I. = ±10 ms)

Note. Sem. = semantically.

parisons were used to establish the amount of priming within each condition. There was significant priming in the semantically related morphological condition [$t_1(79) = 3.77$, $p < .05$; $t_2(29) = 4.03$, $p < .05$] and in the semantically-unrelated morphological condition [$t_1(79) = 3.51$, $p < .05$; $t_2(29) = 2.99$, $p < .05$], but not in the non-morphological form condition [$t_1 < 1$; $t_2 < 1$]. These figures were backed up by analyses that compared priming effects across conditions. Priming effects in the semantically related morphological condition did not differ from those in the semantically-unrelated morphological condition [$t_1 < 1$; $t_2 < 1$]. Conversely, priming effects in the non-morphological form condition differed from those in both the semantically related morphological condition [$t_1(79) = 2.40$, $p < .05$; $t_2(58) = 1.70$, $p < .05$] and the semantically unrelated morphological condition [$t_1(79) = 2.13$, $p < .05$; $t_2(58) = 1.41$, $p = .08$].

The ANOVA on the percentage of errors made across each condition revealed a significant effect of priming [$F_1(1, 78) = 5.11$, $p < .05$; $F_2(1, 84) = 4.40$, $p < .05$; $\min F'(1, 162) = 2.36$, $p = .12$], with fewer errors being made in the primed conditions than in the control conditions. However, there was no interaction between priming and condition [$F_1 < 1$; $F_2 < 2$]. No other effects on the error data reached significance both by subjects and by items, and so these data were not considered any further.

General discussion

Morphological decomposition has typically been seen as a high-level lexical phenomenon constrained by semantic knowledge (e.g., Marslen-Wilson et al., 1994; see also Plaut & Gonnerman, 2000; Rueckl & Raveh, 1999). However, research using the masked priming technique has revealed a form of morphological decomposition operating in the earliest stages of visual word processing that is insensitive to semantic information. This form of morphological decomposition appears instead to be based *solely* on the presence of a morphological structure in the printed stimulus (e.g., legal stem + legal suffix), and as such applies equally to semantically transparent complex words (e.g., darkness), semantically opaque complex words (e.g., corner), and morphologically-structured non-words (e.g., habiter; e.g., Longtin et al., 2003; Longtin & Meunier, 2005; Rastle & Davis, 2003; Rastle et al., 2004).

The aim of this research was to discover more about the nature of this early 'morpho-orthographic' decomposition. Specifically, we sought to discover whether this form-based morphological analysis would break down for stimuli that cannot be perfectly segmented into their morphemic components (as appears to be the case in the non-concatenative morphological system of Hebrew; Frost et al., 2000). Our first three experiments compared masked priming effects when primes were (a) morphologically-complex words that could be parsed perfectly into their morphemic constituents; (b) morphologically-complex words that could not be parsed perfectly into their morphemic constituents because of a missing 'e' at the morpheme boundary (e.g., adorable; Experiment 1), a shared 'e' at the morpheme boundary (e.g., writer; Experiment 2), or a duplicated consonant at the morpheme boundary (e.g., metallic; Experiment 3); and (c) non-morphological form controls (e.g., brothel). Our fourth experiment investigated whether the effects observed in the first three experiments could be extended to pseudo-suffixed stimuli that contain these same orthographic alterations. This experiment compared masked priming effects when primes were (a) semantically transparent morphologically-complex words that contained one of the three orthographic alterations investigated in Experiments 1–3 (e.g., adorable, writer, metallic); (b) pseudo-suffixed words that contained one of these three orthographic alterations (e.g., fetish, badger, committee); and (c) non-morphological form controls (e.g., brothel).

Results of these four experiments were unambiguous. Highly-significant masked morphological priming effects on the order of 25 ms were observed whenever primes were morphologically structured. These priming effects were statistically equivalent for the orthographically transparent and orthographically opaque stimuli used in the first three experiments, and for the semantically transparent and semantically opaque stimuli used in the fourth experiment. Further, the masked morphological priming effects observed in these four experiments were consistently significantly larger than the effects observed for prime–target pairs with non-morphological form overlap. These data bolster the case for a form of morphological decomposition that operates in the early stages of English visual word processing and that is insensitive to semantic information (e.g., Longtin et al., 2003; Longtin & Meunier, 2005; Rastle & Davis, 2003; Rastle et al., 2000, 2004). These data also advance our original findings concerning this form of morphological decomposition, in demonstrating that it is robust to orthographic alterations commonly found in morphologically-complex words.

Before elaborating on the theoretical implications of our findings, it is important to address one potential methodological problem. Though our targets were carefully matched across conditions on factors known to affect visual lexical decision, baseline differences still emerged in *some* of our experiments. Specifically, latencies for targets following unrelated primes tended to be longer in the form condition than in the other two conditions. Some could argue that these baseline differences might make priming effects artificially more difficult to achieve in the form condition, thus undermining our case that the robust priming effects observed in the morphological conditions of our experiments were the result of morpho-orthographic segmentation. To address this potential criticism, we examined the relationship between baseline (control) RT and priming for each item in the two morphological conditions of each experiment. The resulting correlations clearly showed a strong *positive* relationship between baseline RT and priming, such that longer baseline RTs elicited significantly larger priming effects (Experiment 1, $r = .47$; Experiment 2, $r = .64$; Experiment 3, $r = .45$; Experiment 4, $r = .47$). Far from making priming effects more difficult to observe in the form conditions, these analyses suggest that the baseline differences that characterized some of our experiments actually *biased us against* finding more priming in the morphological conditions than in the form conditions.

The key finding from the set of experiments described here is that morphological decomposition in English is robust to regular orthographic alterations found in complex words. This finding supports and elaborates on Taft's (1979) earlier claims regarding the orthographic underspecification of final silent 'e'. Broadly speaking, we can understand the results of Experiment 1 (missing 'e') and Experiment 2 (shared 'e') by embracing the notion that final silent 'e' may be absent from, or somehow marked as optional in, the orthographic representations of stems. In cases of missing 'e' (e.g., adorable) and shared 'e' (e.g., lover), the morphological parser would segment the suffix from the prime stimulus, thus leaving a partial stem matching the (underspecified) orthographic representation of the target. Though Taft (1979) did not discuss the duplication of final consonants in forms like 'drummer', similar principles could be applied to understanding the results of Experiment 3. Specifically, one could suggest that the orthographic representations of stems such as 'drum' are somehow marked as containing an optional additional 'm', and thus become activated in response to exemplars such as 'drumm' (from 'drummer'). Clahsen and colleagues explore a similar notion, arguing that only underspecified lexical entries of stem forms can account for priming patterns observed in German adjectives (Clahsen, Eisenbeiss, Hadler, & Sonnenstuhl, 2001).

One result that we did not necessarily expect was that obtained in Experiment 4. Though we have repeatedly observed masked priming of pseudo-suffixed forms previously (e.g., Gold & Rastle, in press; Lavric et al., 2007; Longtin et al., 2003; Rastle et al., 2004), we wondered whether this group of stimuli would show the same robustness to orthographic alteration as would semantically transparent stimuli. The reason for our scepticism was that many of the stems examined in the pseudo-suffixed condition never surface in genuine morphological relatives in orthographically altered form (e.g., the stem 'fete' never loses its 'e' in a genuine morphological relative). However, a post hoc analysis of this experiment yielded no evidence for any difference in the magnitude of priming between the 23 stems that occur with orthographic alterations (e.g., virtue; mean = 20 ms) and the 7 stems that do not occur with such alterations (e.g., fete; mean = 22 ms). Thus, it seems that orthographic underspecification may be a pre-lexical phenomenon, not dependent on prior experience with orthographically altered stems. This result seems to be consistent with Taft's (1979) claims regarding orthographic underspecification, since he made no distinction between stems that actually occur in altered form and those that do not. Similar results have been obtained in research on phonological underspecification in speech perception (Gaskell et al., 1995; Gaskell & Marslen-Wilson, 1998). For example, it has been shown that phonological inference processes are able to recover the underlying 'n' not only in familiar words like 'lean' in the context 'leam bacon', but also in nonwords like 'threan' in the context 'thream bacon' (Gaskell & Marslen-Wilson, 1998).

To conclude, then, our results provide further evidence that a form of *orthographic* morphological segmentation occurs in the early stages of visual word processing (e.g., Gold & Rastle, in press; Lavric et al., 2007; Longtin et al., 2003; Longtin & Meunier, 2005; Rastle & Davis, 2003; Rastle et al., 2004). Building on these earlier findings, we have shown that this decomposition process is robust to at least some of the regular orthographic alterations found in complex English words, and have put forward some hypotheses about the nature of the orthographic representations of stems that may explain how this robustness is achieved. In some ways our findings seem akin to recent evidence that orthographic representations are robust to minor surface alterations such as letter transpositions (e.g., Perea & Lupker, 2003), evidence that has led a number of researchers (e.g., Davis & Bowers, 2006; Schoonbaert

& Grainger, 2004; Whitney, 2001) to propose orthographic coding schemes that are highly flexible. However, irrespective of the extent to which orthographic representations can tolerate surface variation within stems, it is clear that they cannot tolerate variation across the boundaries of stems and suffixes (Christianson, Johnson, & Rayner, 2005; Duñabeitia, Perea, & Carreiras, in press). Understanding precisely how morpho-orthographic segmentation is achieved will therefore be a critical element in the wider goal of formulating a complete theory of the nature of the orthographic representations used in reading.

Appendix A

Targets followed by related and unrelated masked primes in Experiment 1

Condition	Target	Related prime	Unrelated prime
Transparent form	ALTER	altercation	refrigerate
Transparent form	ANGEL	angelica	mackerel
Transparent form	BAMBOO	bamboozle	soporific
Transparent form	BRASS	brassiere	ultimatum
Transparent form	CELLO	cellophane	rheumatism
Transparent form	CHAR	charm	ankle
Transparent form	COUNTER	counterfeit	sarcophagus
Transparent form	CRAMP	crampon	gingham
Transparent form	DECOR	decorum	syringe
Transparent form	DISC	disco	thorn
Transparent form	EXTRA	extract	crystal
Transparent form	FRANC	franchise	pneumonia
Transparent form	INTER	interim	panache
Transparent form	OPERA	operate	soldier
Transparent form	PLUS	plush	crypt
Transparent form	SALMON	salmonella	centrifuge
Transparent form	SCRAP	scrape	yellow
Transparent form	SHREW	shrewd	kidney
Transparent form	SNIP	snipe	udder
Transparent form	SPUR	spurn	ethos
Transparent form	STIR	stirrup	phoenix
Transparent form	SURGE	surgeon	romance
Transparent form	TREAT	treatise	sardonic
Transparent form	VERB	verbose	rubella
Transparent form	VISA	visage	jockey
Transparent form	AMEN	amend	spade
Transparent form	AURA	aural	igloo
Transparent form	BASIL	basilica	plimsoll
Transparent form	CANDID	candidacy	alabaster
Transparent form	CHANCE	chancellor	distribute
Transparent form	CORPUS	corpuscle	nutriment
Transparent form	COUP	coupon	retina
Transparent form	CROQUET	croquette	introvert
Transparent form	DETER	detergent	aluminium
Transparent form	ETHER	ethereal	pilchard
Transparent form	FOREST	forestall	intrinsic
Transparent form	HEART	hearth	topple
Transparent form	JERK	jerkin	nozzle
Transparent form	PLAIN	plaintiff	rectangle
Transparent form	RATIO	ration	puddle
Transparent form	SCOUR	scourge	ceramic
Transparent form	SHOVE	shovel	lizard
Transparent form	SINCE	sincere	cherish
Transparent form	SPRIG	sprightly	conundrum
Transparent form	STERN	sternum	crinkle
Transparent form	STUB	stubble	amnesty

(*continued on next page*)

Appendix A (*continued*)

Condition	Target	Related prime	Unrelated prime
Transparent form	TACIT	taciturn	renovate
Transparent form	TWIN	twine	scald
Transparent form	VILLA	villain	astound
Transparent form	WREN	wrench	tailor
Transparent morphological	ALIEN	alienate	hardship
Transparent morphological	AUDIT	auditor	idyllic
Transparent morphological	BUZZ	buzzer	yearly
Transparent morphological	COMBAT	combatant	navigator
Transparent morphological	DEFER	deference	limitless
Transparent morphological	DREAM	dreamless	laughable
Transparent morphological	ENJOY	enjoyable	migration
Transparent morphological	FIEND	fiendish	solvency
Transparent morphological	FLUFF	fluffy	marker
Transparent morphological	FROTH	frothy	mugger
Transparent morphological	GLOOM	gloomy	tribal
Transparent morphological	GUARD	guardian	secondly
Transparent morphological	HUMID	humidity	neatness
Transparent morphological	INHABIT	inhabitant	comparable
Transparent morphological	JAZZ	jazzy	ducal
Transparent morphological	MAGIC	magician	humorous
Transparent morphological	MOURN	mourner	bedding
Transparent morphological	ODD	oddity	rugged
Transparent morphological	ORANGE	orangeade	herbalist
Transparent morphological	QUIET	quieten	movable
Transparent morphological	SPLASH	splashy	masonic
Transparent morphological	SURF	surfer	lamely
Transparent morphological	TOPIC	topical	spender
Transparent morphological	VENOM	venomous	urbanize
Transparent morphological	VOCAL	vocalist	systemic
Transparent morphological	ASH	ashen	scaly
Transparent morphological	BEEF	beefy	usage
Transparent morphological	CHEMIST	chemistry	organizer
Transparent morphological	DAMN	damning	zealous
Transparent morphological	DIET	dietary	woollen
Transparent morphological	EGO	egoism	skimpy
Transparent morphological	EVICT	eviction	silencer
Transparent morphological	FILTH	filthy	darken
Transparent morphological	FREAK	freaky	oldish
Transparent morphological	FUZZ	fuzzy	piper
Transparent morphological	GROUND	groundless	contrition
Transparent morphological	HEIR	heiress	suction
Transparent morphological	INFECT	infection	awareness
Transparent morphological	INSIST	insistent	traumatic
Transparent morphological	KNOCK	knocker	squeaky
Transparent morphological	MOTOR	motorist	rhythmic
Transparent morphological	MYTH	mythical	inventor
Transparent morphological	OIL	oily	hazy
Transparent morphological	PREACH	preacher	feverish
Transparent morphological	SELF	selfish	voltage
Transparent morphological	STEAM	steamer	realism
Transparent morphological	TOAST	toaster	florist
Transparent morphological	TRESPASS	trespasser	remorseful
Transparent morphological	VIOLIN	violinist	regulator
Transparent morphological	WIDOW	widowed	creator
Opaque form	BULB	bulge	realm
Opaque form	OCCUR	occult	frugal
Opaque form	RUBY	rubble	willow

Appendix A (*continued*)

Condition	Target	Related prime	Unrelated prime
Opaque form	MODEL	modern	create
Opaque form	PILLAR	pillage	glutton
Opaque form	FISH	fissure	avocado
Opaque form	WHEEL	wheedle	torpedo
Opaque form	CHUTE	chutney	shampoo
Opaque form	SOLID	solicit	ammonia
Opaque form	OPTIC	optimum	dormant
Opaque form	BLISS	blister	replica
Opaque form	SCREEN	screech	bouquet
Opaque form	COUNT	counsel	pasture
Opaque form	SATIN	satisfy	release
Opaque form	MAGNET	magnesia	incubate
Opaque form	CHAPEL	chaperon	accolade
Opaque form	TRAVEL	travesty	catalyst
Opaque form	BARBER	barbecue	fugitive
Opaque form	PARADE	paradigm	tentacle
Opaque form	SQUIRT	squirrel	chaplain
Opaque form	STRAND	strangle	distress
Opaque form	STRAIN	straight	indicate
Opaque form	MARSH	marsupial	buccaneer
Opaque form	BLAST	blasphemy	marijuana
Opaque form	CHALK	challenge	efficient
Opaque form	TROT	trowel	kennel
Opaque form	CLEAR	cleave	stitch
Opaque form	ALLEY	allege	pistol
Opaque form	CRUMB	crumpet	ruffian
Opaque form	STENCH	stencil	machete
Opaque form	BUTTON	buttock	frigate
Opaque form	ANCHOR	anchovy	epitaph
Opaque form	WHITE	whittle	monsoon
Opaque form	TRUNK	trundle	algebra
Opaque form	PEACE	peacock	gallant
Opaque form	SPARK	sparrow	methane
Opaque form	VETO	veteran	sulphur
Opaque form	RELIC	relieve	harbour
Opaque form	PASTRY	pastrami	splutter
Opaque form	MERIT	meringue	amethyst
Opaque form	PLANT	plankton	cavalier
Opaque form	PRISM	pristine	hyacinth
Opaque form	GRAFT	graffiti	mandarin
Opaque form	MOSQUE	mosquito	syndrome
Opaque form	SPRINT	sprinkle	handicap
Opaque form	COLLAR	collapse	instinct
Opaque form	BARRACK	barracuda	mistletoe
Opaque form	CARNAL	carnation	lubricate
Opaque form	HURRY	hurricane	synthesis
Opaque form	TERRACE	terracotta	ostensible
Opaque morphological	GRANULE	granular	dilution
Opaque morphological	FIBRE	fibrous	cashier
Opaque morphological	PROBE	probing	starchy
Opaque morphological	CYCLE	cyclist	postage
Opaque morphological	SERENE	serenity	township
Opaque morphological	NUDE	nudity	orator
Opaque morphological	URINE	urinate	voyager
Opaque morphological	OBESE	obesity	envious
Opaque morphological	SMILE	smiling	learner
Opaque morphological	OPPOSE	opposite	mystical

(*continued on next page*)

Appendix A (*continued*)

Condition	Target	Related prime	Unrelated prime
Opaque morphological	LUSTRE	lustrous	royalist
Opaque morphological	TUBE	tubing	porous
Opaque morphological	SIZE	sizable	thicken
Opaque morphological	WHALE	whaling	scruffy
Opaque morphological	LODGE	lodging	outward
Opaque morphological	CLOSE	closure	infancy
Opaque morphological	VIRTUE	virtuous	downward
Opaque morphological	AMUSE	amusing	fighter
Opaque morphological	ADORE	adoration	hideously
Opaque morphological	PURPLE	purplish	leisured
Opaque morphological	AMAZE	amazing	musical
Opaque morphological	GLOBE	global	openly
Opaque morphological	OBLIGE	obligate	vaporize
Opaque morphological	ROGUE	roguish	painful
Opaque morphological	TRUE	truly	sixty
Opaque morphological	ELEVATE	elevator	likeness
Opaque morphological	IMITATE	imitator	sewerage
Opaque morphological	SATIRE	satirical	personify
Opaque morphological	ERASE	erasure	juggler
Opaque morphological	FALSE	falsity	blender
Opaque morphological	STYLE	stylist	freshen
Opaque morphological	FORGIVE	forgivable	beautician
Opaque morphological	PLEASE	pleasant	suitable
Opaque morphological	AGILE	agility	mindful
Opaque morphological	SEVERE	severity	emphatic
Opaque morphological	SCARCE	scarcity	hangover
Opaque morphological	SECURE	security	physical
Opaque morphological	SMOKE	smoking	faintly
Opaque morphological	FARCE	farcical	infusion
Opaque morphological	MOBILE	mobilize	examiner
Opaque morphological	GLANCE	glancing	artistry
Opaque morphological	VALUE	valuable	survival
Opaque morphological	QUOTE	quotation	readiness
Opaque morphological	GAMBLE	gambling	betrayal
Opaque morphological	SCHEME	schematic	publicist
Opaque morphological	CUBE	cubic	toxic
Opaque morphological	NERVE	nervous	victory
Opaque morphological	POLLUTE	pollution	landscape
Opaque morphological	TRIFLE	trifling	anarchic
Opaque morphological	TYPE	typical	payment

Appendix B

Targets followed by related and unrelated masked primes in Experiment 2

Condition	Target	Related prime	Unrelated prime
Form	AMEN	amend	spade
Form	BROTH	brothel	turmoil
Form	DECOR	decorum	syringe
Form	EXTRA	extract	abolish
Form	FOREST	forestall	pneumonia
Form	INFER	inferno	pumpkin
Form	MANIFEST	manifesto	prescribe
Form	OPERA	operate	soldier
Form	PLUS	plush	bilge
Form	RATIO	ration	puddle

Appendix B (*continued*)

Condition	Target	Related prime	Unrelated prime
Form	SCRAP	scrape	humble
Form	WEIR	weird	swamp
Form	STRIP	stripe	plague
Form	TWIN	twine	scald
Form	BLUR	blurb	viola
Form	COMMA	command	pretend
Form	CROQUET	croquette	introvert
Form	DRIVE	drivel	bunion
Form	FORCE	forceps	typhoon
Form	HEART	hearth	mosaic
Form	INTER	interim	panache
Form	MOMENT	momentum	thorough
Form	PLAN	plank	choir

Appendix B (*continued*)

Condition	Target	Related prime	Unrelated prime
Form	QUART	quartz	attire
Form	SCOUR	scourge	ceramic
Form	SHOVE	shovel	lizard
Form	SOMBRE	sombrero	barnacle
Form	SHREW	shrewd	cotton
Form	MARINA	marinade	semester
Opaque	ADMIRE	admirer	harmful
Opaque	CHASE	chaser	eggcup
Opaque	DIVERGE	divergent	lamplight
Opaque	ERASE	eraser	catnap
Opaque	GLIDE	glider	tiptoe
Opaque	LANCE	lancer	groovy
Opaque	MERGE	merger	facial
Opaque	PICTURE	picturesque	colonialism
Opaque	PURSUE	pursuer	womanly
Opaque	SKATE	skater	entrap
Opaque	STATUE	statuette	telepathy
Opaque	TEASE	teaser	woeful
Opaque	URGE	urgent	nearby
Opaque	WEAVE	weaver	uptake
Opaque	WHITE	whiten	mislay
Opaque	CARVE	carver	floppy
Opaque	DANCE	dancer	insane
Opaque	FUSE	fused	kinky
Opaque	JOKE	joker	nutty
Opaque	LOOSE	loosen	midday
Opaque	MUSCLE	muscled	soloist
Opaque	PRINCE	princess	workshop
Opaque	RESIDE	resident	organism
Opaque	SMOKE	smoker	grimly
Opaque	SUBSIDE	subsidence	neglectful
Opaque	TITLE	titled	purist
Opaque	VALUE	valuer	avidly
Opaque	WHALE	whaler	laxity
Opaque	WRITE	writer	handle
Transparent	OIL	oily	hazy
Transparent	JAZZ	jazzy	dopey
Transparent	FUZZ	fuzzy	hilly
Transparent	FREAK	freaky	skimpy
Transparent	THORN	thorny	limply
Transparent	SPEED	speedy	typify
Transparent	GLOOM	gloomy	sticky
Transparent	GUILT	guilty	reform
Transparent	SHIVER	shivery	dustpan
Transparent	BABY	babyish	florist
Transparent	SWEEP	sweeper	minibus
Transparent	SPEAK	speaker	besides
Transparent	DRAIN	drainage	abnormal
Transparent	DEFEND	defender	motorway
Transparent	PUBLISH	publisher	courtyard
Transparent	ITCH	itchy	relay
Transparent	FISH	fishy	weedy
Transparent	FUSS	fussy	gaily
Transparent	SUGAR	sugary	breezy
Transparent	CHALK	chalky	hopper
Transparent	FLUFF	fluffy	tiring
Transparent	FILTH	filthy	eyelid
Transparent	SPLASH	splashy	aridity
Transparent	POWDER	powdery	failing
Transparent	SPIDER	spidery	keyhole
Transparent	WEALTH	wealthy	cooking
Transparent	HUMID	humidity	grasping
Transparent	ATTACK	attacker	solemnly
Transparent	TERROR	terrorism	continual

Appendix C

Targets with related and unrelated masked primes in Experiment 3

Condition	Target	Related prime	Unrelated prime
Form	ALTER	altercation	refrigerate
Form	FUSE	fuselage	marjoram
Form	BRASS	brassiere	ultimatum
Form	CELLO	cellophane	rheumatism
Form	CROQUET	croquette	introvert
Form	DEMON	demonstrate	instruction
Form	DISC	disciple	material
Form	ENTER	entertain	guarantee
Form	FORCE	forceps	lampoon
Form	HABIT	habitat	quarrel
Form	LAVA	lavatory	molecule
Form	COUNTER	counterfeit	sarcophagus
Form	SOMBRE	sombrero	gargoyle
Form	TRAMP	trampoline	salamander
Form	VISA	visage	jockey
Form	ANGEL	angelica	mackerel
Form	BASIL	basilica	plimsoll
Form	BUTT	buttress	gelatine
Form	FOREST	forestall	intrinsic
Form	CRAMP	crampon	gingham
Form	HEART	hearth	topple
Form	DRIVE	drivel	emetic
Form	EXTRA	extract	crystal
Form	BROTH	brothel	turmoil
Form	CHANCE	chancellor	distribute
Form	PARENT	parenthesis	chlorophyll
Form	SCOUR	scourge	ceramic
Form	MANIFEST	manifesto	prescribe
Form	TWIN	twinkle	aspirin
Form	PLAIN	plaintiff	rectangle
Opaque	BEGIN	beginner	displace
Opaque	DROP	dropper	bigotry
Opaque	EQUIP	equipped	gardener
Opaque	FORGET	forgettable	inattention
Opaque	KIDNAP	kidnapper	invisibly
Opaque	LIBEL	libellous	noiseless
Opaque	METAL	metallic	dogmatic
Opaque	PANEL	panelling	outspread
Opaque	PROPEL	propeller	firsthand
Opaque	SPLIT	splitting	picnicker
Opaque	STRIP	stripper	heatedly
Opaque	SWIM	swimmer	trooper
Opaque	OCCUR	occurrence	vegetarian

(*continued on next page*)

Appendix C (*continued*)

Condition	Target	Related prime	Unrelated prime
Opaque	TRAVEL	traveller	certainty
Opaque	WRAP	wrapper	fluency
Opaque	CONTROL	controller	enthusiast
Opaque	DRUM	drummer	shyness
Opaque	FORBID	forbidden	admirable
Opaque	JEWEL	jewellery	amazement
Opaque	KNOT	knotty	minnow
Opaque	MEDAL	medallion	arresting
Opaque	MODEL	modeller	dynastic
Opaque	PLAN	planner	amusing
Opaque	REBEL	rebellion	injustice
Opaque	STIR	stirring	unevenly
Opaque	STUN	stunning	unsettle
Opaque	THROB	throbbing	cavernous
Opaque	TRANSMIT	transmitter	secretarial
Opaque	WORSHIP	worshipper	fraudulent
Opaque	KNIT	knitting	paranoid
Transparent	ALIEN	alienate	boarding
Transparent	DEFEND	defender	advisory
Transparent	BLISS	blissful	feckless
Transparent	DRAIN	drainage	adultery
Transparent	ENJOY	enjoyable	migration
Transparent	BLIND	blindness	phosphate
Transparent	CHEER	cheerless	sculpture
Transparent	DOUBT	doubtful	headline
Transparent	LISTEN	listener	greeting
Transparent	MOTOR	motorist	rhythmic
Transparent	MYTH	mythical	permeate
Transparent	PEACE	peaceful	literacy
Transparent	REGION	regional	producer
Transparent	STAIN	stainless	electrify
Transparent	TEMPT	temptation	privileged
Transparent	GREEN	greenery	harmonic
Transparent	FIEND	fiendish	gatepost
Transparent	DEVIL	devilish	flagship
Transparent	HUMID	humidity	neatness
Transparent	VENOM	venomous	urbanize
Transparent	BRIGHT	brightness	retrospect
Transparent	CLEAR	clearance	dignified
Transparent	EVICT	eviction	accustom
Transparent	MAGIC	magician	humorous
Transparent	MOURN	mournful	playmate
Transparent	NOVEL	novelist	grouping
Transparent	ADAPT	adaptation	distortion
Transparent	ROYAL	royalist	energize
Transparent	STIFF	stiffness	recollect
Transparent	VOCAL	vocalist	thruster

Appendix D

Targets with related and unrelated masked primes in Experiment 4

Condition	Target	Related prime	Unrelated prime
Form	BROTH	brothel	serpent
Form	ENTER	entertain	pronounce
Form	COMMA	command	missile

Appendix D (*continued*)

Condition	Target	Related prime	Unrelated prime
Form	SOMBRE	sombrero	espresso
Form	SHOVE	shovel	drench
Form	SLEEK	sleeve	junior
Form	CHAPEL	chaperon	fluoride
Form	LETHAL	lethargy	nicotine
Form	PARADE	paradox	disrupt
Form	PLANT	plankton	trespass
Form	SEVEN	severe	double
Form	SPARK	sparrow	incense
Form	SQUID	squirm	walnut
Form	REGRET	regress	tadpole
Form	TRAVEL	travesty	renegade
Form	CROQUET	croquette	demarcate
Form	STAMP	stampede	carousel
Form	SCOUR	scourge	cashier
Form	RATIO	ration	census
Form	MANIFEST	manifesto	prescribe
Form	STATUS	statute	torment
Form	CHART	charge	second
Form	MELODY	melodrama	badminton
Form	ATTACK	attache	chariot
Form	RADIO	radical	lecture
Form	APPLY	applaud	dwindle
Form	SQUEAL	squeamish	trilobite
Form	STENCH	stencil	ruffian
Form	TEMPT	tempest	custard
Form	TROUT	trouser	deplete
Sem. unrelated	COMMIT	committee	knowledge
Sem. unrelated	SURGE	surgery	amusing
Sem. unrelated	JADE	jaded	sulky
Sem. unrelated	BADGE	badger	cosmic
Sem. unrelated	ANGLE	angler	crowded
Sem. unrelated	TRUE	truancy	playpen
Sem. unrelated	SALUTE	salutary	humidity
Sem. unrelated	PALATE	palatial	jubilant
Sem. unrelated	CURATE	curative	fetching
Sem. unrelated	POLITE	politic	sunless
Sem. unrelated	EMPIRE	empirical	ingenuity
Sem. unrelated	MODULE	modulate	absentee
Sem. unrelated	SUBLIME	sublimate	telepathy
Sem. unrelated	COMMODE	commodity	inability
Sem. unrelated	PRIVATE	privation	overspill
Sem. unrelated	SMUG	smuggle	manhood
Sem. unrelated	DECADE	decadence	profusion
Sem. unrelated	TUBE	tuber	jerky
Sem. unrelated	CLOVE	clover	uphold
Sem. unrelated	STRIDE	strident	loathing
Sem. unrelated	OPERATE	operatic	forewarn
Sem. unrelated	SUPPLE	supplant	viscount
Sem. unrelated	FETE	fetish	shifty
Sem. unrelated	VIRTUE	virtual	mockery
Sem. unrelated	STRANGE	strangle	greeting
Sem. unrelated	MARINE	marinate	homespun
Sem. unrelated	TEMPLE	template	lucidity
Sem. unrelated	ALLEGE	allegory	logistic
Sem. unrelated	SUBSIDE	subsidize	gathering
Sem. unrelated	VERSE	version	rapidly

Appendix D (*continued*)

Condition	Target	Related prime	Unrelated prime
Sem. related	CRYSTAL	crystalline	documentary
Sem. related	DIVERGE	divergent	bloodshot
Sem. related	REFUGE	refugee	eyebrow
Sem. related	TITLE	titled	hourly
Sem. related	SCENE	scenery	closure
Sem. related	PULSE	pulsate	seating
Sem. related	FARCE	farcical	nightcap
Sem. related	FUSE	fusion	saying
Sem. related	POLLUTE	pollutant	viability
Sem. related	URINE	urinate	mystify
Sem. related	GLOBE	global	inside
Sem. related	ATHLETE	athletic	devotion
Sem. related	IMPULSE	impulsive	someplace
Sem. related	ADVISE	advisory	gardener
Sem. related	IMAGINE	imaginary	landowner
Sem. related	SWIM	swimmer	outpost
Sem. related	GLIDE	glider	creamy
Sem. related	INTERFERE	interference	neighbouring
Sem. related	DANCE	dancer	insane
Sem. related	DRIVE	driver	mostly
Sem. related	VACCINE	vaccinate	defeatist
Sem. related	CAPTIVE	captivate	insertion
Sem. related	DEDUCE	deducible	broadcast
Sem. related	CUBE	cubic	dizzy
Sem. related	FERTILE	fertilize	aggravate
Sem. related	MATURE	maturity	disclose
Sem. related	SERVE	servant	failure
Sem. related	RELATE	relation	customer
Sem. related	STYLE	stylish	moonlit
Sem. related	PREJUDICE	prejudicial	opinionated

Note. Sem. = semantically.

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