

# ERP Evidence of Morphological Analysis from Orthography: A Masked Priming Study

Aureliu Lavric<sup>1</sup>, Amanda Clapp<sup>1</sup>, and Kathleen Rastle<sup>2</sup>

## Abstract

■ There is broad consensus that the visual word recognition system is sensitive to morphological structure (e.g., “hunter” = “hunt” + “er”). Moreover, it has been assumed that the analysis of morphologically complex words (e.g., “hunter”) occurs only if the meaning of the complex form can be derived from the meanings of its constituents (e.g., “hunt” and “er”). However, recent behavioral work using masked priming has suggested that morphological analysis can occur at an early, orthographic level, with little influence from semantics. The present investigation examined the neurophysiological correlates of masked priming in conditions of a genuine morphological relationship (e.g., “hunter”–“HUNT”), an apparent

morphological relationship (“corner”–“CORN”), and no morphological relationship (“brothel”–“BROTH”). Neural priming was indexed by the reduction of the N400 ERP component associated with targets preceded by related primes, as compared to targets preceded by unrelated primes. The mere appearance of morphological structure (“corner”–“CORN”) resulted in robust behavioral and neural priming, whose magnitude was similar to that observed in pairs with genuine morphological relationship and greater than that in the nonmorphological pairs. The results support a purely structural morphemic segmentation procedure operating in the early stages of visual word perception. ■

## INTRODUCTION

Morphemes have traditionally been seen as minimal units of meaning, which can be combined to create words (Hockett, 1958). Only a small proportion of English words comprise a single stem morpheme (e.g., *play*). The much larger proportion of English words are built by combining these stem morphemes either with other stem morphemes (e.g., *playgroup*) or with prefixes and suffixes (e.g., *playful*, *replay*). Morphemes have an important place in the characterization of alphabetic languages because they provide structure to the generally arbitrary mapping between the orthographic and phonological forms of words and their meanings (e.g., Plaut & Gonnerman, 2000; Bybee, 1985). Rarely do words that comprise similar letters have similar meanings (e.g., *cat*, *rat*, *car*, *cut*, *bat*). Morphemes provide an exception to this arbitrariness because (a) letters corresponding to stems occur repeatedly in forms that have similar meanings (e.g., *trust*, *trusting*, *distrust*) and (b) letters corresponding to prefixes and suffixes alter the meanings of stems in relatively predictable ways (e.g., *played*, *trusted*, *walked*; Rastle, Davis, Marslen-Wilson, & Tyler, 2000).

Following approximately 30 years of debate (e.g., Taft, 1981; Taft & Forster, 1975), there is now relatively wide

agreement that morphologically complex words are represented in a “decomposed” manner (i.e., in terms of their constituent morphemes) in visual word recognition. Morphological decomposition is supported by numerous studies showing that words derived from high-frequency stems are recognized more quickly than words derived from low-frequency stems (e.g., measured as lexical decision times, Schreuder & Baayen, 1997; or fixation duration, Niswander, Pollatsek, & Rayner, 2000; see also Taft, 2004, for extensions of this basic morphemic frequency effect). Further evidence comes from the observation that the recognition of a printed target such as *DEPART* is facilitated when it is preceded by either a derivationally related prime (e.g., *departure*) or an inflectionally related prime (e.g., *departing*) more than is expected based on their overlap in form or meaning (e.g., Rastle et al., 2000; Drews & Zwitserlood, 1995; Stolz & Feldman, 1995; Bentin & Feldman, 1990; Stanners, Neiser, Hernon, & Hall, 1979). Finally, support for morphological decomposition comes from studies that distinguish brain event-related potentials (ERPs) elicited by the decomposable regular past tense inflection (*call*–*called*) from those elicited by the nondecomposable irregular past tense inflection (*see*–*saw*) (see Lavric, Pizzagalli, Forstmeier, & Rippon, 2001, for a review).

Although theorists agree on the evidence supporting morphological decomposition, they disagree on how this decomposition occurs in the reading system. “Classical” theories (e.g., Giraudo & Grainger, 2000;

<sup>1</sup>University of Exeter, UK, <sup>2</sup>Royal Holloway, University of London, UK

Marslen-Wilson, Tyler, Waksler, & Older, 1994) postulate a level at which morphemic units are represented explicitly and at which morphologically complex words are segmented into their constituents. Distributed-connectionist theories (e.g., Davis, van Casteren, & Marslen-Wilson, 2003; Plaut & Gonnerman, 2000; Rueckl & Raveh, 1999; Rueckl, Mikolinsky, Raveh, Miner, & Mars, 1997), by contrast, do not postulate an explicit level of morphological representation, but instead develop highly similar representations for morphologically complex words and their stems in the hidden units mediating orthographic and semantic representations (see Rastle et al., 2000, for a discussion). Morphological structure emerges in these distributed-connectionist models as a consequence of the consistency that morphologically complex words bring to the mapping between orthography and meaning. Despite these differences in their characterizations of morphological decomposition, however, both of these theoretical frameworks explain morphological effects in terms of overlap in the (local or distributed) representations of morphologically complex words and their respective stems.

### Morphological Analysis in the Absence of Semantics?

One important theoretical commitment shared by these approaches to morphological processing concerns the influence of semantic transparency on morphological decomposition. Irrespective of how morphological decomposition is conceptualized, there has been relative agreement that morphologically complex words share representations with their stems only in cases in which there is a semantic relationship between them (Marslen-Wilson et al., 1994; see also Davis et al., 2003; Giraudo & Grainger, 2000; Plaut & Gonnerman, 2000; Rueckl & Raveh, 1999; Rueckl et al., 1997). For example, all these theories of morphological processing would take the view that representations of *darkness* and *dark* overlap to a much greater degree than the representations of *witness* and *wit* (which are etymologically related, but are no longer semantically related) or *corner* and *corn* (which are not semantically or, despite appearances, etymologically related). Thus, morphological effects (e.g., morphological priming effects, morphemic frequency effects) are typically expected according to these theories only in cases in which a morphologically complex word and its stem are semantically related. Support for this perspective on morphological decomposition has come primarily from behavioral research using tasks thought to reflect semantic levels of processing (e.g., cross-modal priming: Longtin, Segui, & Halle, 2003; Marslen-Wilson et al., 1994; visual priming with fully visible primes: Rastle et al., 2000; and unprimed visual lexical decision: Ford, Marslen-Wilson, & Davis, 2003).

Despite empirical support for semantically constrained morphological decomposition, recent evidence

using the masked priming technique (e.g., Forster & Davis, 1984) has pointed to a form of morphological decomposition that operates without regard to semantic information. Rastle, Davis, and New (2004) compared masked priming effects on visual lexical decision (using a stimulus-onset asynchrony [SOA] of 42 msec) across three conditions: (a) a “transparent” condition in which primes were morphologically and semantically related to their stems (e.g., *darkness*–*DARK*); (b) a “form” condition in which semantically unrelated primes and targets had a nonmorphological orthographic relationship (e.g., *brothel*–*BROTH*; –el never functions as an English suffix); and (c) an “opaque” condition in which primes and targets had an apparent morphological relationship (i.e., they comprised the stem target plus a legal suffix; e.g., *corner*–*CORN*) but no semantic relationship. The opaque condition included some etymologically related items (e.g., *archer*–*ARCH*), but this was not a requirement (hereafter, the use of “opaque” will not imply an etymological relationship). Rastle et al. (2004) found greater priming in the transparent and opaque conditions than in the nonmorphological form condition (e.g., both *darkness*–*DARK* and *corner*–*CORN* pairs yielded more priming than *brothel*–*BROTH* pairs), and found statistically indistinguishable priming effects in the transparent and opaque conditions (e.g., *darkness*–*DARK* and *corner*–*CORN* pairs yielded equivalent priming). These and other similar empirical findings (e.g., Longtin & Meunier, 2005; Longtin et al., 2003; Rastle & Davis, 2003) seem to implicate a form of morphological decomposition operating in visual word processing that is blind to the semantic characteristics of a stimulus, and that is based instead on the mere *appearance* of morphological complexity (e.g., existing stem + existing affix).

There is good reason to believe that the form of decomposition described by Rastle et al. (2004) characterizes a very early stage of visual word processing, certainly one that precedes the activation of semantic information. Most importantly, behavioral evidence for this form of decomposition seems to surface *only* when primes are masked and presented so briefly (e.g., 40 msec) that they are unavailable for conscious report—the very conditions in which comparable semantic priming effects (e.g., violin–CELLO) are small and unreliable (Rastle et al., 2000).<sup>1</sup> Under conditions in which primes are fully visible (and in which semantic priming effects are generally more robust; Rastle et al., 2000), behavioral evidence for the form of decomposition that is semantically constrained is instead observed: Semantically transparent pairs (e.g., *darkness*–*DARK*) alone show strong facilitatory effects, with semantically opaque pairs (e.g., *corner*–*CORN*) and nonmorphological form controls (e.g., *brothel*–*BROTH*) yielding unreliable priming effects that tend toward inhibition (Rastle et al., 2000). This group of findings raises the prospect that the representations activated by briefly presented

masked primes are representations of known orthographic forms (see, e.g., Davis & Lupker, 2006; Davis, 2003), and that these representations are themselves structured in terms of familiar morphemic units (Davis, 2004; Rastle et al., 2004; Rastle & Davis, 2003).

### Using ERPs to Examine Morphological Analysis

The present investigation employs the ERP technique to examine morphological processing. There is already some ERP evidence consistent with the proposal that there is a form of morphological decomposition that arises early in visual word processing, prior to the activation of semantic information. Two recent studies conducted in Spanish compared priming effects using fully visible primes (250 msec) in stem homograph pairs (e.g., *rata-RATO*; rat-moment) with priming effects in morphologically related pairs (e.g., *loca-LOCO*; mad-woman-madman) (Dominguez, de Vega, & Barber, 2004; Barber, Dominguez, & de Vega, 2002). Behavioral effects were consistent with other long SOA visual priming studies (e.g., Rastle et al., 2000): Robust priming effects emerged only for the semantically related morphological pairs. However, intriguing effects were found in the N400 component of the ERP waveform, previously shown to be sensitive to lexico-semantic information (e.g., Holcomb, Reder, Misra, & Grainger, 2005; Kiefer, 2002; Kutas & Federmeier, 2000). Specifically, Dominguez et al. (2004) and Barber et al. (2002) found that in the early part of the N400 temporal window, both morphologically related pairs and stem homograph pairs were associated with an attenuated N400 relative to the N400 elicited by unrelated words (*pavo-META*, turkey-goal). Later in the ERP segment, the N400 for morphologically related pairs remained reduced, whereas the N400 for stem homographs increased, reaching the same amplitude as that in the unrelated condition. Thus, morphologically related pairs elicited an unambiguous attenuation of N400. In contrast, stem homographs were associated with a biphasic N400 modulation: an early reduction in N400, followed by an increase. Importantly, the replacement of stem homographs (*rata-RATO*) with form-related control pairs (*rasa-RANA*) did not result in the same biphasic N400 modulation, suggesting that the early N400 attenuation observed for stem homographs was not merely an effect of letter overlap.

The biphasic ERP effect seen for stem homograph primes (reduction, followed by an increase in N400) in these studies is suggestive of an early stage of morphological decomposition that is independent of semantics, followed by a stage in which access to semantics eliminates neural priming in the semantically unrelated stem homographs. The goal of our study was to discover whether we could isolate a pattern of N400 attenuation consistent with semantically independent morphological decomposition by using briefly presented masked

primes (the presentation conditions that elicit this form of decomposition in behavioral studies; Rastle et al., 2000, 2004; Longtin et al., 2003). Like Rastle et al. (2004), we compared masked priming effects for semantically transparent pairs (e.g., *darkness-DARK*), semantically opaque pairs (e.g., *corner-CORN*), and nonmorphological form pairs (e.g., *brothel-BROTH*). Based on the suggestive findings of Dominguez et al. (2004) and Barber et al. (2002), our expectation was that the semantically transparent and semantically opaque primes would yield equivalent attenuation of the N400 component in response to their respective targets (relative to unrelated control primes), and that this reduction in the N400 component would be greater than that yielded by non-morphological form primes.<sup>2</sup>

The pattern of data predicted in this study would constitute the first unambiguous neurophysiological evidence for a form of morphological decomposition that is insensitive to semantic information. However, this study may also have more general implications in respect of recent controversy regarding the form of processing reflected by N400. Specifically, showing that N400 can be influenced by the morpho-orthographic structure of a consciously imperceptible stimulus would add to the increasing body of evidence disputing Brown and Hagoort's (1993) assertion that N400 reflects conscious, postlexical integration processes alone (e.g., Holcomb et al., 2005; Kiefer, 2002; Deacon, Hewitt, Yang, & Nagata, 2000). This demonstration would instead suggest that N400 can be sensitive to the unconscious, automatic processes characterizing the earliest stages of visual word perception, and which are engaged in the activation of stored orthographic knowledge (see also Holcomb et al., 2005).

## METHODS

### Participants

Twenty-four students from the University of Exeter, all right-handed native speakers of English, provided informed written consent to take part in the study. Two participants' data were excluded from the analysis due to excessive artifact in the electroencephalogram (EEG). The remaining 22 participants had a mean age of 21.86 years, with a range spanning 19 to 30 years; 12 of them were women and 10 were men.

### Stimuli

One hundred ninety-eight prime-target pairs were selected from the Celex English database (Baayen, Piepenbrock, & van Rijn, 1993). Sixty-six pairs were selected for each of three conditions: transparent, opaque, and form. The item set was based largely on that used by Rastle et al. (2004), with only a few additions and replacements. Each prime-target pair in the transparent condition had a

morphological relationship that was also semantically transparent (e.g., *magical*–*MAGIC*). Prime–target pairs in the opaque condition had an apparent morphological relationship but no semantic relationship (e.g., *compassion*–*COMPASS*). Each prime in the transparent and opaque conditions could be parsed perfectly into its stem target and a frequently occurring English suffix. Prime–target pairs in the form condition had an orthographic relationship, but no semantic or apparent morphological relationship (e.g., *brothel*–*BROTH*). Primes within the form condition comprised the stem target plus a non-morphological ending. Nonmorphological endings were those not used as English suffixes or used only very infrequently as English suffixes (i.e., in no more than four orthographically transparent words such as –n in *silvern*). Most of the transparent primes were derivations of their targets and most of the opaque primes contained derivational suffixes. Only 3 out of the 66 transparent primes can be seen as inflections of their targets (adopted; alarming; widowed) and only 4 used suffixes found in inflections (bearded; scalding; teething; tufted). Only three primes (out of 66) in the opaque condition contained pseudo-suffixes that can be used as inflections (crooked; fleeting; grueling). After testing, it was found that three items from the form condition (*against*–*AGAIN*, *tactile*–*TACT*, and *textile*–*TEXT*) were incorrectly classified as nonmorphological and were therefore removed from statistical analyses; all item statistics reported hereafter exclude these items.

The targets were matched as closely as possible across conditions for target frequency, target length, and target neighborhood size, whereas primes were matched for prime frequency (see Table 1). Prime–target pairs were matched as closely as possible for form overlap (the number of target letters divided by the number of prime letters), and conditions were distinguished appropriately from one another in terms of prime–target semantic relatedness. The Latent Semantic Analysis Web facility (Landauer & Dumais, 1997; location <http://lsa.colorado.edu/>) was used to compute the semantic relatedness for each prime–target pair in the three experimental conditions.<sup>3</sup> LSA similarity values did not

differ between form and opaque conditions [ $F(1, 119) = 0.023$ , *ns*], but were greater for the transparent pairs than the opaque pairs [ $F(1, 121) = 101.71$ ,  $p = .001$ ] and the form pairs [ $F(1, 118) = 98.975$ ,  $p = .001$ ]. To reduce the overall prime–target relatedness to 37%, 66 unrelated prime–target pairs were included (see Rastle et al., 2004).

Unrelated suffixed control primes were selected for each of the target words. Control primes were semantically, orthographically, and morphologically unrelated to targets, and were matched as closely as possible to related primes on frequency and length [ $t(394) = 0.336$ , *ns*;  $t(394) = 0.037$ , *ns*, respectively]. There were also 264 nonword targets, which were preceded by suffixed English words (hereon referred to as nonword target pairs). Nonword targets were matched to word targets on length [ $F(3, 461) = 1.568$ , *ns*]. For counterbalancing purposes, there were two stimulus lists. Each list contained all 198 experimental targets; half of the targets in each list were preceded by related primes and half were preceded by control primes. Each list contained all of the nonword target pairs and all of the unrelated filler pairs. Each participant saw one list only and participated in each of the three experimental conditions. Thus, across all participants, the same targets were used in related and control pairs.

## Procedure

Stimuli, presented in randomized order for each participant using E-Prime software (Psychology Software Tools, Pittsburgh, USA), subtended a visual angle of 2.25°–3.27° horizontally and 0.49°–0.65° vertically. Participants were told that they would be seeing a series of hashes (mask, presented for 500 msec), which would be replaced by a letter string in uppercase (target, presented until a response was made or for 1500 msec). They were not informed of the presence of the lowercase prime presented for 42 msec between the mask and the target. Participants made a word/nonword response to the target by pressing a key with their right or left hand, respectively. Ten practice trials were run before testing started.

**Table 1.** Stimulus Statistics

Statistic	Condition			ANOVA
	Form	Opaque	Transparent	
Target frequency	36.22	42.32	48.10	$F(2, 192) = 0.633$ , <i>ns</i>
Prime frequency	20.11	44.52	20.68	$F(2, 192) = 2.120$ , <i>ns</i>
Target length	4.76	4.95	5.00	$F(2, 192) = 2.176$ , <i>ns</i>
Target neighborhood	2.38	1.82	1.95	$F(2, 192) = 2.589$ , <i>ns</i>
Form overlap	0.67	0.68	0.69	$F(2, 192) = 1.265$ , <i>ns</i>

The target and prime frequency values are the frequency per million, taken from the Celex English database (Baayen et al., 1993).



## EEG Acquisition

The EEG was acquired with an elastic cap with 64 embedded Ag/AgCl electrodes (ElectroCap International, Eaton, Ohio) and BrainAmpMR amplifiers (Brain Products, Munich, Germany). There were 58 electrodes on the scalp in an extended 10–20 configuration, two on the outer canthi of the eyes, two above and below the orbit of each eye, and two on the earlobes. The placement of the cap was adjusted with a CMS-20EP ultrasound digitizer (Zebris Medical, Isny, Germany). The EEG was sampled at 500 Hz with a bandpass of 0.016–100 Hz (reference, Cz; ground, AFz). Off-line, data were filtered (0.1–40 Hz; 24 dB/oct) and re-referenced to the averaged ears.

## ERP Analysis

ERP segments of 600 msec (plus a 100-msec prestimulus baseline) were time-locked to the onset of targets associated with a correct response. Epochs containing eye, muscle, and other artifact were removed from the subsequent analyses. Artifact-free, baseline-corrected ERPs were averaged within each condition (transparent, opaque, form) and prime type (related, control) for groups of electrodes to yield average amplitudes for five scalp regions on the left: anterior frontal (Fp1, AF3, F1, F3, F5, F7), posterior frontal (FC1, FC3, FC5, C1, C3, C5), temporal (T7, TP7, CP5, P7), parietal (CP1, CP3, P1, P3, P5), and parietal–occipital (PO1, PO3, PO7, O1), and the corresponding regions on the right; midline electrodes were not analyzed.

For a detailed investigation of N400, analyses were run on the mean amplitude within four 40-msec time windows spanning this component: 340–380, 380–420, 420–460, and 460–500 msec. Three other consecutive 40-msec time windows in the earlier part of the ERP, in which substantial related versus control prime differences were noted, were also analyzed (140–180, 180–220, 220–260 msec).

Repeated-measures analyses of variance (ANOVAs, henceforth referred to as Omnibus) with factors morphology (three conditions: transparent, opaque, form), prime type (two conditions: related, control), region (five scalp regions), and hemisphere (two) were run for each of the above windows. When reliable interactions between condition and prime type were found, follow-up ANOVAs (Prime type  $\times$  Region  $\times$  Hemisphere) were performed to assess the presence of priming effects in each condition. If in the latter ANOVAs prime type interacted with region and/or hemisphere, *t* tests were run to contrast related and control primes in individual scalp regions. Spherical spline interpolation was used to represent topographies in figures (Figures 3 and 4).

Potential differences in the topography of the priming effects were examined as follows. Related minus control

difference waves were computed for each condition. To disambiguate topographic effects from ERP amplitude effects, difference waves were scaled using the vector length method (McCarthy & Wood, 1985) and submitted to 3 (morphology)  $\times$  5 (region)  $\times$  2 (hemisphere) ANOVAs.

In the ANOVAs, the Huynh–Feldt correction for sphericity violations was applied; corrected *p* values and uncorrected degrees of freedom are reported. In the N400 analysis, prior knowledge was used to maximize statistical power in *t* tests: *t* tests were restricted to the posterior scalp regions where N400 is known to manifest itself (temporal, parietal, and parietal–occipital), and the expectation that priming is associated with a reduction of N400 amplitude permitted one-tailed *t* tests. This gain in power enabled the use of the Bonferroni correction (in each time window separately) for multiple *t* tests, which were run when reliable interactions between condition and scalp region and/or hemisphere were found. Because early ERP correlates of priming are less understood, *t* tests run in early time windows (between 140 and 260 msec) could not benefit from prior knowledge. Because this had an impact on statistical power (all scalp regions had to be examined, and only two-tailed tests could be employed), we report uncorrected *t* tests from the early time windows.

## RESULTS

### Behavioral Results

Response times (RTs) and errors were analyzed in a two-stage procedure (see Table 2). First, the presence of reliable priming in each condition was assessed by means of *t* tests comparing responses to targets preceded by related primes to those preceded by control primes. Second, differential priming in the three conditions was assessed by ANOVA with factors morphology (transparent, opaque and form) and list (two lists of items, each subject was exposed to one), as well as *t* tests that compared the magnitude of the priming in different conditions.

**Table 2.** Mean Response Time (RT, in msec) and Error Rate (%) to Targets, and the Priming Effect for Each of the Two Measures

	Condition					
	Form		Opaque		Transparent	
	RT	Errors	RT	Errors	RT	Errors
<i>Preceded By:</i>						
Related prime	714	7.5	675	5.1	650	0.8
Control prime	723	8.7	700	5.5	682	3.0
Priming effect	9	1.2	25	0.4	32	2.2

## Response Times

Robust priming was found in the transparent and opaque pairs [ $t(21) = 7.32, p < .001$ ;  $t(21) = 3.21, p < .01$ , respectively], but not in the form pairs [ $t(21) = 1.42, ns$ ]. Further, ANOVA revealed a significant main effect of morphology on priming, [ $F(2, 40) = 3.540, p < .05$ ]. The analyses of the magnitude of priming revealed significantly greater priming in the transparent pairs than in the form pairs [ $t(21) = 3.215, p < .01$ ] and greater priming in the opaque pairs than in the form pairs [ $t(21) = 1.690, p = .05$ , one-tailed], but no reliable difference in priming between the opaque and the transparent pairs [ $t(21) = 0.642, ns$ ]. Thus, the study replicated the behavioral effects reported by Rastle et al. (2004).

## Error Data

Robust priming was found only in the transparent pairs [ $t(21) = 3.65, p < .01$ ], but not in the opaque and form pairs. No reliable differences between levels of the factor, morphology, in the magnitude of priming were detected in the ANOVA and subsequent  $t$  tests.

## ERP Results

### N400 (340–500 msec)

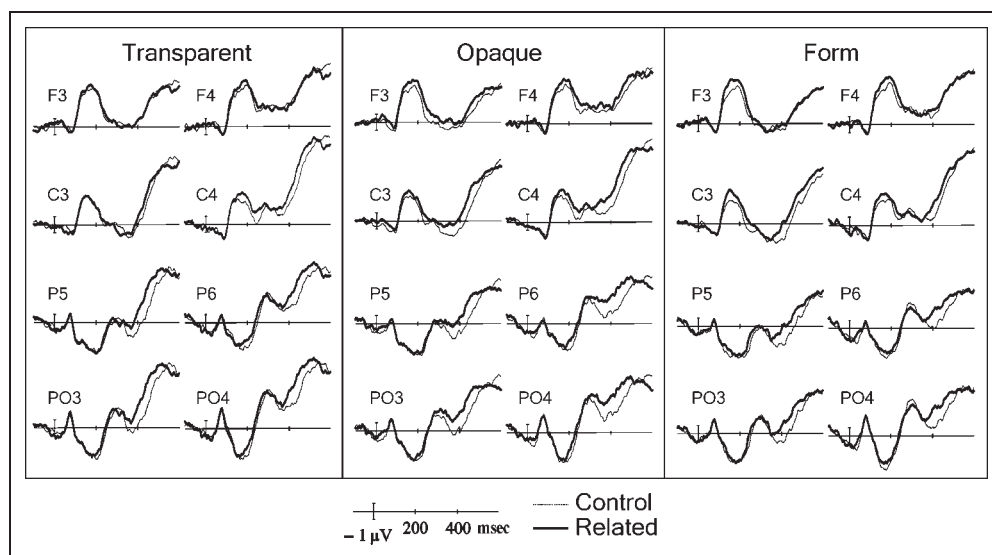
An examination of the ERP differences in the N400 range points to a reduction of the N400 to targets preceded by related primes compared to those preceded by control primes (see Figure 1). This was reflected in the reliable main effect of prime type in the Omnibus ANOVAs in all four time windows: 340–380 msec [ $F(1, 21) = 4.19, p = .05$ ]; 380–420 msec [ $F(1, 21) = 15.46, p = .001$ ]; 420–

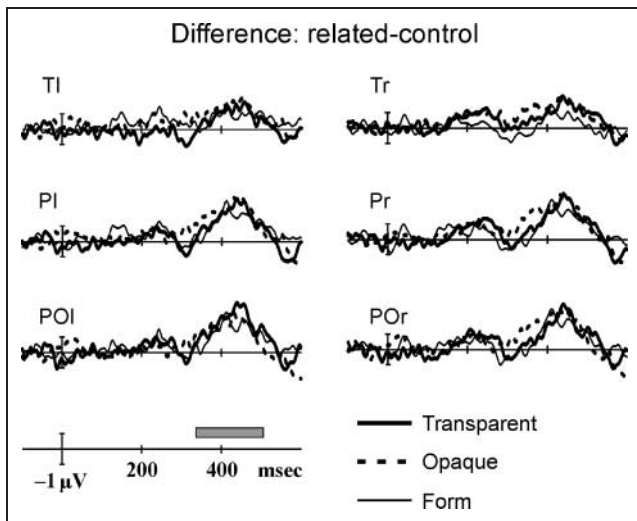
460 msec [ $F(1, 21) = 14.33, p = .001$ ]; 460–500 msec [ $F(1, 21) = 6.04, p < .05$ ]. In the context of the present investigation, the critical effects are interactions involving the factors morphology and prime type, which would indicate that N400 attenuation is differential across the three levels of morphology (the transparent, opaque, and form conditions). Reliable interactions involving these two factors were found in the 340–380 msec and in the 460–500 msec time windows.

The Omnibus ANOVA performed on mean ERP amplitude in the 340–380 msec time window found a reliable Morphology  $\times$  Prime type  $\times$  Region  $\times$  Hemisphere interaction [ $F(8, 168) = 2.41, p < .05$ ], indicating that the N400 reduction is not the same across conditions (see Figures 2 and 3), an effect that may be particularly manifest in some regions of the scalp. Follow-up (condition-wise) ANOVAs revealed in this time window a reliable main effect of Prime type in the opaque condition [ $F(1, 21) = 8.13, p = .01$ ] and a reliable Prime type  $\times$  Region  $\times$  Hemisphere interaction in the transparent condition [ $F(4, 84) = 2.73, p < .05$ ], the latter followed by a reliable region-wise  $t$  test in the transparent condition in the left parietal–occipital region [ $t(21) = 2.68, p < .05$ , one-tailed, corrected]. No reliable reduction in the N400 amplitude was found in the form condition in this time window, as indexed by the ANOVA effects involving the factor prime type [Prime type:  $F(1, 21) = 0.99$ ; Prime type  $\times$  Region:  $F(4, 84) = 0.41$ ; Prime type  $\times$  Hemisphere:  $F(4, 84) = 1.06$ ; Prime type  $\times$  Region  $\times$  Hemisphere:  $F(4, 84) = 2.08$ , all  $ns$ ].

In the 460–500 msec window, Omnibus ANOVA revealed a significant interaction between morphology, prime type, region, and hemisphere [ $F(8, 168) = 2.32, p < .05$ ] pointing to a differential N400 attenuation across conditions, which was manifest differentially in the five regions and two sides of the scalp. Follow-up

**Figure 1.** ERPs in the three conditions at representative electrode sites.





**Figure 2.** Difference waves averaged over six scalp regions: TI = temporal left; Tr = temporal right; PI = parietal left; Pr = parietal right; POI = parietal-occipital left; POOr = parietal-occipital right. The N400 difference is more pronounced in the transparent and opaque conditions than in the form condition. The gray bar above the time axis indicates the time range submitted to statistical analyses.

ANOVAs in this time window revealed a reliable main effect of prime type in the opaque condition [ $F(1, 21) = 4.31, p = .05$ ] and a reliable Prime type  $\times$  Region interaction in the transparent condition [ $F(4, 84) = 3.77, p < .05$ ], followed by a marginally significant  $t$  test in the left parietal-occipital region [ $t(21) = 2.47, p = .06$ , one-tailed, corrected]. As in the 340–380 msec time window, no reliable priming was found in the form condition, as indicated by effects involving the factor prime type that failed to reach significance [Prime type:  $F(1, 21) = 2.88$ ; Prime type  $\times$  Region:  $F(4, 84) = 2.98$ ; Prime type  $\times$  Hemisphere:  $F(4, 84) = 0.36$ ; Prime type  $\times$  Region  $\times$  Hemisphere:  $F(4, 84) = 2.43$ , all *ns*].

The above interactions between morphology, prime type, region, and hemisphere in the Omnibus ANOVAs may be indicative of differences in the topography of the N400 effect across conditions. However, ANOVAs on unscaled ERP amplitudes are known to conflate amplitude and topography effects (McCarthy & Wood, 1985). We therefore used a procedure that is more appropriate for testing for topographic differences: vector length scaling (McCarthy & Wood, 1985). The scaled (control minus related) difference waves were examined with ANOVA in each of the four time windows in the N400 range. Two sets of ANOVAs were run: one with three levels on the factor morphology (transparent, opaque, form) and one with two levels (transparent, opaque). The latter was run to ascertain potential topographic divergence between transparent and opaque priming not detected in the analysis with all three levels. Both sets of ANOVAs found topographic differences only in one of the four time windows (460–500 msec), as in-

dicated by the reliable Morphology  $\times$  Region  $\times$  Hemisphere interaction [Morphology factor, 3 levels:  $F(8, 168) = 2.21, p < .05$ ; Morphology factor, 2 levels:  $F(4, 84) = 3.94, p = .01$ ].

To summarize, in the transparent and opaque conditions, N400 was reliably attenuated by priming in all four time windows in the 340–500 msec range, whereas in the form condition, reliable N400 attenuation was found only in two time windows (380–420 and 420–460 msec) (see Figures 2 and 3). In one of the four time windows (the last: 460–500 msec), there were differences in the scalp distribution of the priming effect in the transparent and opaque conditions.

#### Early Time Windows (140–260 msec)

The ERP waveform was more positive-going for targets preceded by related primes compared to those preceded by control primes (see Figures 1 and 4). This was confirmed by Omnibus ANOVA, which found a main effect of prime type in all three 40-msec time windows [ $F(1, 21) = 4.42, p < .05$ ;  $F(1, 21) = 4.57, p < .05$ ;  $F(1, 21) = 7.74, p = .01$ ].

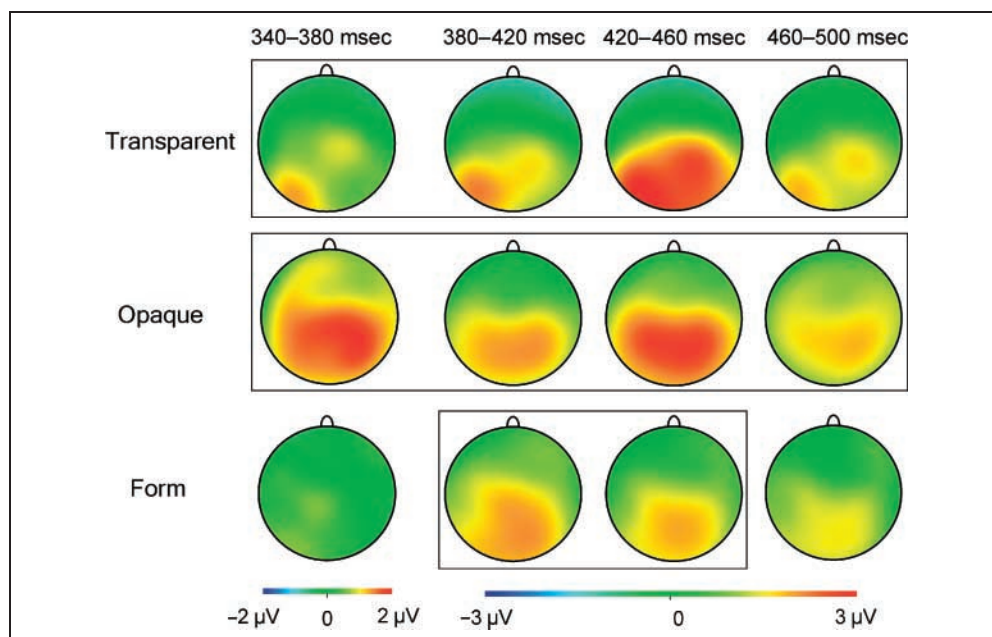
The critical interactions, those involving morphology and prime type, were reliable or marginally reliable in two time windows: 180–220 msec [Morphology  $\times$  Prime type  $\times$  Hemisphere:  $F(2, 42) = 2.99, p = .06$ ; Morphology  $\times$  Prime type  $\times$  Region  $\times$  Hemisphere,  $F(8, 168) = 3.52, p < .01$ ] and 220–260 msec [Morphology  $\times$  Prime type  $\times$  Hemisphere [ $F(2, 42) = 4.37, p < .05$ ; Morphology  $\times$  Prime type  $\times$  Region  $\times$  Hemisphere,  $F(8, 168) = 3.42, p < .01$ ].

Follow-up (condition-wise) ANOVAs in the 180–220 msec time window found that prime type interacted with the factors region and hemisphere in each of the three conditions: transparent [ $F(4, 84) = 3.20, p < .05$ ], opaque [ $F(4, 84) = 3.71, p < .05$ ], and form [ $F(4, 84) = 2.98, p = .05$ ]. In the transparent condition, a Prime type  $\times$  Hemisphere interaction was also reliable [ $F(1, 21) = 6.01, p < .05$ ]. These interactions raise the possibility that, despite a nonsignificant main effect of prime type in all condition-wise ANOVAs, a local reliable priming effect may be present in some/all conditions. In the transparent condition, this effect was reliable in the right temporal region [ $t(21) = 2.06, p = .05$ , uncorrected]; in the form condition, it was reliable in the left anterior frontal region [ $t(21) = 2.09, p < .05$ , uncorrected]; and in the opaque condition,  $t$  tests were significant in both of the above regions [left anterior frontal,  $t(21) = 2.24, p < .05$ ; right temporal,  $t(21) = 2.59, p < .05$ , both uncorrected].

Follow-up (condition-wise) analyses in the 220–260 msec time window found reliable Prime type  $\times$  Hemisphere [ $F(1, 21) = 6.18, p < .05$ ] and Prime type  $\times$  Region  $\times$  Hemisphere [ $F(4, 84) = 3.98, p < .05$ ] interactions in the transparent condition, a main effect of prime type [ $F(1, 21) = 5.80, p < .05$ ] in the opaque con-



**Figure 3.** The scalp distribution of the related-minus-control differences in the N400 component. In all three conditions, the ERP to the targets preceded by related primes is more positive-going, that is, N400 is attenuated. Rectangles indicate the time windows in which the N400 reduction is statistically significant. In the form condition, this effect is late to emerge (as seen in the 340–380 msec window) and fades out more rapidly at longer latencies (460–500 msec).



dition, and a Prime type  $\times$  Region  $\times$  Hemisphere interaction in the form condition that neared significance [ $F(4, 84) = 3.98, p = .08$ ]. Uncorrected  $t$  tests were significant in the right posterior frontal, right temporal, and right parietal regions in the transparent condition [ $t(21) = 2.17, p < .05; t(21) = 2.45, p < .05; t(21) = 2.41, p < .05$ ]; and the left anterior frontal, left posterior frontal, and left temporal regions in the form condition [ $t(21) = 2.09, p < .05; t(21) = 2.24, p < .05; t(21) = 2.29, p < .05$ ].

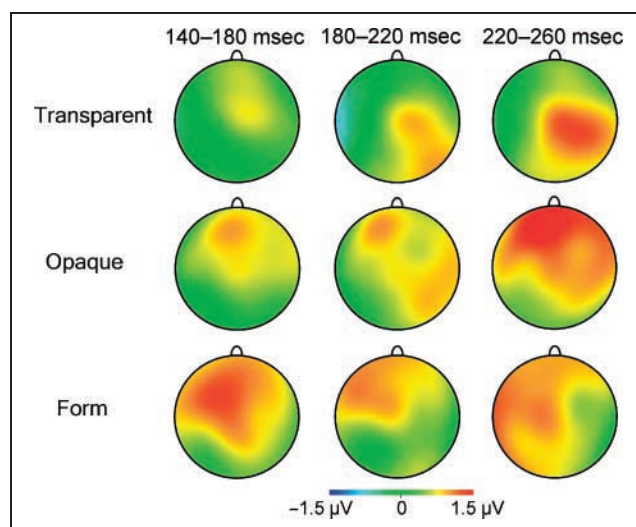
Topographical analyses using scaled difference waves, run in all three time windows, revealed reliable differences in the topography of the priming effect in the 220–260 msec time window. The Morphology (three levels: transparent, opaque, form)  $\times$  Region  $\times$  Hemisphere ANOVA found a reliable Morphology  $\times$  Hemisphere interaction [ $F(2, 42) = 4.27, p < .05$ ] and a reliable Morphology  $\times$  Region  $\times$  Hemisphere interaction [ $F(8, 168) = 3.49, p < .05$ ]. Follow-up analyses, run on pairs of conditions (transparent vs. opaque, transparent vs. form, opaque vs. form), found that the scalp distribution of the priming effect was reliably different in the transparent versus form conditions, as indicated by the Morphology  $\times$  Hemisphere [ $F(1, 21) = 7.06, p < .05$ ] and Morphology  $\times$  Region  $\times$  Hemisphere [ $F(4, 84) = 7.72, p < .01$ ] interactions. The priming effect in the opaque condition could not be topographically distinguished from the effects in either the transparent condition or the form condition.

In summary, a reliable effect of prime type was found throughout the 140–260 msec range in each of the three conditions. Between 220 and 260 msec, there were reliable differences between the transparent and form conditions in the scalp distribution of this effect: It was confined to the right posterior scalp in the transparent

condition and to the left anterior scalp in the form condition (see Figure 4). In the opaque condition, the effect of prime type was found both in the left anterior and in the right posterior scalp regions.

## DISCUSSION

The objective of the present investigation was to test at the neurophysiological level the proposal recently put forward (Rastle et al., 2004; Longtin et al., 2003; Rastle & Davis, 2003) that an early analysis of morphological



**Figure 4.** The scalp distribution of the related-minus-control amplitude differences in the early part of the ERP.



structure occurs at the orthographic level, with little or no contribution from semantics. Previous ERP research investigating long SOA priming in Spanish had given some support to this idea (Dominguez et al., 2004; Barber et al., 2002). These studies found a reduction in the early part of the N400 component of target recognition that was equivalent for stem homograph pairs (which had an apparent morphological relationship) and transparent morphological pairs. In the latter part of the N400 range of target recognition, the N400 for morphologically related pairs stayed attenuated, whereas the N400 to stem homographs increased in amplitude, presumably because of the semantic incongruity between the targets and the fully visible primes.

However, to demonstrate unequivocally that morphological analysis can operate with little or no influence from semantics, one has to show that in conditions that severely limit access to the semantics of the prime, the mere appearance of morphological structure will lead to neural priming of a similar magnitude to that observed when a true morphological relationship is present. In attempting such a demonstration, we followed Rastle et al. (2004) by comparing the magnitude of masked priming effects in three experimental conditions: transparent morphological (e.g., *cleaner*–*CLEAN*), nonmorphological form (e.g., *brothel*–*BROTH*), and opaque morphological (e.g., *corner*–*CORN*). As in other ERP studies (Holcomb et al., 2005; Dominguez et al., 2004; Barber et al., 2002), our principal measure of neural priming was the degree of attenuation in the N400 component of the ERP in response to the targets preceded by the related primes as compared to those preceded by the unrelated primes. We also investigated the onset of the ERP differences elicited by our priming manipulation by examining the earlier part of the ERP segment. Behaviorally, our results closely replicated the outcomes of Rastle et al. (2004) (see also Longtin et al., 2003): Significant and statistically indistinguishable RT priming effects were observed in the transparent and opaque conditions, and both of these conditions showed reliably more priming than the form condition.

At the neurophysiological level, we predicted a more pronounced N400 attenuation by transparent and opaque priming relative to form priming, but a similar pattern of N400 reduction in the former two conditions. The results supported this prediction. In the transparent and opaque conditions, N400 to targets was attenuated in all four time windows of the analyzed N400 range (340–500 msec) when a related prime was presented previously, as compared to presenting a control prime (see Figures 2 and 3). In contrast, in the form condition, the N400 reduction was only observed between 380 and 460 msec. Thus, neural priming indexed by N400 developed later and was more short-lived in the form condition relative to the transparent and opaque conditions. To our knowledge, this is the first ERP investi-

gation of masked morphological priming. The results from the analysis of the N400 component support early, orthography-based, morphemic segmentation (Rastle et al., 2004; Longtin et al., 2003). Our results indicate a similar magnitude of priming in the transparent and opaque conditions with only subtle differentiation between these two conditions—the topographic difference found in one (the last) of the four time windows of the N400 range. It is difficult to know how to interpret this limited difference, although one possibility is that it arose from variations in the visibility of the primes over trials or subjects (cf. Holcomb et al., 2005). Such variations could have allowed limited semantic processing, a possibility not inconsistent with the somewhat reduced (though not reliably so) magnitude of RT priming in the opaque pairs relative to the transparent pairs.

A recent study (Devlin, Jamison, Matthews, & Gonnerman, 2004) employed a similar short SOA masked priming paradigm to compare neural priming, measured as blood-oxygen-level-dependent functional magnetic resonance imaging signal reduction, in morphologically related pairs (*bunter*–*HUNT*) with that observed in orthographically related (*corner*–*CORN*) and semantically related (*imitate*–*COPY*) pairs. Brain areas that showed signal reduction in response to morphologically related pairs (left angular and middle temporal gyri, left occipito-temporal cortex) overlapped substantially with those showing signal reduction in response to orthographically related pairs (left angular gyrus, left occipito-temporal cortex) and semantically related pairs (left angular and middle temporal gyri). Because Devlin et al.'s (2004) orthographic condition consisted largely of pairs that we conceptualize as having an opaque morphological relationship (e.g., *corner*–*CORN*), it is tempting to explain the overlap in the brain regions deactivated in the morphological and orthographic conditions (e.g., left occipito-temporal cortex) in terms of the involvement of an early morpho-orthographic segmentation mechanism in these two conditions. However, Devlin et al.'s design did not separate the pairs with an opaque morphological relationship from those related only in form (e.g., *brothel*–*BROTH*). The present investigation successfully addresses this limitation, thus enabling the distinction between surface overlap and morphological (genuine or apparent) relationship.

In addition to the N400 attenuation, we have also identified an ERP effect of prime type at earlier latencies: Between circa 140 and 260 msec, the ERP waveform was more positive for targets preceded by related primes as compared to those preceded by control primes (see Figures 1 and 4). This early positivity was detected reliably in all three conditions. Reliable topographic differences were found in the last time window (220–260 msec) between the topographies of the priming effect in the transparent and form conditions. This could

be an effect of morphological structure (primes in the transparent condition are morphologically complex, whereas those in the form condition are not), with the ERP difference reflecting early morphological segmentation. However, it could also be an effect of semantics (primes in the transparent condition are semantically related to their targets, whereas those in the form condition are not). The topography of the priming effect in the opaque condition could not be distinguished statistically from the topographies in the transparent or form conditions. Considering the effects in the N400 range and the behavioral results, we favor the morphological interpretation; however, the ambiguity of the topography in the opaque condition precludes us from drawing firm conclusions regarding the priming effect in the early part of the ERP segment.

Although our data only contain direct evidence regarding derivational processes (most of the relevant primes were derivations or pseudo-derivations), we believe that our theoretical interpretation can be generalized to other domains of morphology, such as inflectional morphology and compound morphology. The already-mentioned study by Dominguez et al. (2004) used inflections and pseudo-inflections in their comparison of morphological pairs and stem homograph pairs; the fact that, in the initial phase, the N400 response to stem homographs paralleled that to morphological pairs supports early morpho-orthographic segmentation of inflections. Similarly, the masked priming research of Shoolman and Andrews (2003) yielded results consistent with the morpho-orthographic segmentation of transparent (e.g., *bookshop*), partially opaque (e.g., *jaywalk*), and pseudo-morphological (e.g., *hammock*) compounds (see also Zwitserlood, 1994).

To conclude, the present study probed for neural correlates of early morphological analysis, which is independent of semantic information. It is the first investigation to examine masked neural priming in conditions of genuine and apparent morphological relationship. Like the behavioral findings of Rastle et al. (2004) (see also Longtin et al., 2003), more pronounced N400 attenuation by transparent and opaque primes relative to form primes, but equivalent N400 reduction in the former two cases, implicate a purely structural morphemic segmentation procedure operating in the early stages of visual word perception.

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Reprint requests should be sent to Aureliu Lavric, School of Psychology, University of Exeter, Exeter EX4 4QG, UK, or via e-mail: [a.lavric@exeter.ac.uk](mailto:a.lavric@exeter.ac.uk); URL: <http://www.centres.ex.ac.uk/pmrrc/individual/aureliu.html>.

### Notes

1. There have been various claims made that printed stimuli undergo semantic processing under subliminal presentation conditions (e.g., Reynvoet, Brysbaert, & Fias, 2002; Dehaene et al., 1998; Draine & Greenwald, 1998; Perea & Gotor, 1997; Greenwald, Draine, & Abrams, 1996; Marcel, 1983). However, these claims have been disputed on several levels. For one, several of these claims have been based on priming experiments involving highly restricted prime sets (e.g., numbers from 1 to 9; Reynvoet et al., 2002; Dehaene et al., 1998), in which the formation of automatized stimulus–response mappings that bypass conceptual analysis is possible (Damian, 2001). Other claims of unconscious semantic processing have been based on priming experiments that use associates (e.g., Marcel, 1983); priming effects between genuine category coordinates are much more difficult to find, unless primes are classified in visible form prior to subliminal presentation (e.g., Draine & Greenwald, 1998). In the rare cases in which genuine semantic priming effects that do not involve prior conscious manipulation of the prime have been observed (e.g., Perea & Gotor, 1997), prime exposure durations have usually been in the range of partial visibility (67 msec), and could thus be explained through conscious processing of some proportion of the trials (see also Holcomb et al., 2005). To our knowledge, there is no evidence for genuine semantic priming effects on lexical decision under the strict presentation conditions in which this form of morphological decomposition has been observed.
2. This prediction may seem inconsistent with reports of masked semantic priming effects on the N400 component of target recognition (e.g., Kiefer, 2002; Deacon et al., 2000). However, these effects have been usually observed using longer SOA conditions than are used in our experiment (see also Perea & Gotor, 1997); the effects are much smaller under the 40-msec SOA conditions used here (Holcomb et al., 2005). Thus, even if masked presentation conditions do not block semantic processing entirely, the weight of evidence suggests that they do limit it considerably.
3. Some word pairs were not included in the analysis because they were not in the LSA database: two word pairs in the form condition (*twitch*–*TWIT*, *marinade*–*MARINA*), two word pairs in the opaque condition (*brisket*–*BRISK*, *trumpet*–*TRUMP*), and four word pairs in the transparent condition (*nymphet*–*NYMPH*, *oxygenate*–*OXYGEN*, *floatier*–*FLOAT*, *quieten*–*QUIET*).

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