

What do fully visible primes and brain potentials reveal about morphological decomposition?

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Abstract

To examine the role of meaning in morphological decomposition ({re-}+{play}), researchers have employed the priming paradigm. Perceptually masked primes lead to facilitation both when decomposition is semantically appropriate (*hunter-HUNT*) and when it is not (*corner-CORN*), whereas with fully visible primes facilitation is observed only in the former case. We investigated the N400 brain potential time-locked to words preceded by fully visible primes. At ~300–380 ms, N400 was equally attenuated in the semantically “transparent” condition (*hunter-HUNT*) and semantically “opaque” condition (*corner-CORN*). In the transparent condition, N400 remained attenuated after 380 ms, whereas in the opaque condition it returned to the level of a nonmorphological form condition (*brothel-BROTH*). This pattern of N400 priming is consistent with an orthography-based, morphological decomposition mechanism, “licensed” at a later stage by semantic information.

Descriptors: Morphology, Priming, Decomposition, N400, ERP

One key issue in the study of word recognition and reading is that of the segmentation (or *decomposition*) of words into their constituent parts (or *morphemes*), as in *playful*, *replay*, *player*, *played*, and so forth. Usually, we think of words as being decomposable if they are related in meaning to their morphemic constituents; for example, whereas *replay* is easily decomposed into {re-}+{play}, it seems much more difficult to think about *reward* as consisting of the morphemes {re-}+{ward}. Furthermore, the semantic relationship between morphologically complex words and their stems is largely systematic, that is, the relationship between *player* and *play* is similar to that between *hunter* and *hunt*. It is therefore unsurprising that most theories of morphological decomposition (Girardo & Grainger, 2000; Plaut & Gonnerman, 2000; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rueckl, Mikolinski, Raveh, Miner, & Mars, 1997) postulate that segmentation is contingent on the semantic relationship between the morphologically complex form and its stem. Although the above theories make contrasting claims regarding the manner in which morphological decomposition occurs (e.g., only some of them postulate explicit representations of morphemes), they share the assumption that semantics plays a key role in morphological decomposition.

Evidence for this assumption comes from several paradigms. For example, zero-lag priming studies using fully visible primes (Rastle, Davis, Marslen-Wilson, & Tyler, 2000) have found facilitatory effects of morphologically complex primes on processing of their stems presented as targets (e.g., *departure-DEPART*) as long as the relationship between prime and target is semantically “transparent”; no facilitation has been observed when the semantic relationship between prime and target is semantically “opaque” for historical reasons (e.g., *apartment-APART*). Cross-modal (Longtin, Segui, & Hallé, 2003; Marslen-Wilson et al., 1994; Meunier & Longtin, 2007) and long-lag (e.g., Drews & Zwitserlood, 1995; Marslen-Wilson & Zhou, 1999; Rueckl & Aicher, 2008) priming studies have also distinguished between prime–target pairs with a semantically transparent relationship and those in which such relationship is absent (including etymologically related words such as *apartment-APART* and pseudo-derivations such as *corner-CORN*; henceforth, we will apply the term “opaque” to both of these cases).

However, a different picture of morphological decomposition emerges from studies that use the masked-priming paradigm, in which primes presented for very brief durations (40–50 ms) are sandwiched between forward and backward mask stimuli, and in which the backward mask is typically the target presented in a different case to the prime. Studies using this procedure have yielded significant and equivalent facilitation of target processing in both semantically transparent (e.g., *darkness-DARK*) and semantically opaque (e.g., *corner-CORN*) conditions, with priming in both of these conditions being significantly larger than that observed when primes and targets have a nonmorphological form relationship only (e.g., *brothel-BROTH*; -el never functions as a suffix in English). These masked-priming effects originally

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reported by Longtin et al. (2003) and Rastle, Davis, and New (2004) have since been confirmed by a substantial number of studies (see Rastle & Davis, 2008, for a review). The finding of comparable priming in conditions of genuine (e.g., *darkness-DARK*) and apparent (e.g., *corner-CORN*) morphological structure suggests an early morphological decomposition mechanism, reliant on orthographic input and oblivious to semantic influences. This conclusion is consistent with the earliest accounts of morphological processing (Taft, 1981; Taft & Forster, 1975), according to which decomposition is achieved through sublexical orthographic analysis that occurs indiscriminately in transparent (e.g., *hunter*) and opaque (e.g., *corner*) words alike.

The evidence so far is thus somewhat contradictory. Semantic transparency appears to have an influence on morphological decomposition in priming paradigms in which primes are available to conscious perception but has no influence on morphological decomposition in priming paradigms in which primes are masked and presented very briefly. This discrepancy has led investigators to propose (a) that there may be two levels of the reading system at which morphologically complex words are decomposed (with one level of decomposition being orthographically based and one level of decomposition being semantically based; e.g., Rastle et al., 2004) or (b) that there is a single level of orthographically based decomposition that is refined through a “licensing stage” of analysis at which the appropriateness of morphemic decompositions is assessed (with inappropriate segmentations like *corner* → {*corn*} + {*-er*} being ruled out at this later stage of analysis; e.g., Meunier & Longtin, 2007). However, an alternative possibility that must be considered is that the evidence for a semantically based form of decomposition is not as compelling as it appears to be. Indeed, as pointed out by Rastle and Davis (2008), neither long stimulus onset asynchrony (SOA) priming (e.g., Rastle et al., 2000) nor long-lag priming (e.g., Rueckl & Aicher, 2008) have been able to distinguish priming in morphologically related pairs (e.g., *departure-depart*) from priming effects in which pairs are semantically and orthographically related (e.g., *lunch-brunch*). It thus remains possible that these priming effects do not arise from a morphological relationship but are a consequence of the semantic and orthographic relationship characteristic of semantically transparent morphologically complex words.

ERP Studies of Masked Morphological Priming

Recently, researchers have started to exploit the high temporal resolution and some well-documented components of brain potential recordings (ERPs) to investigate the role of semantic processing in morphological decomposition. Two studies have used masked priming to examine the effects of semantic transparency on morphological priming in lexical decision (Lavric, Clapp, & Rastle, 2007; Morris, Frank, Grainger, & Holcomb, 2007). Lavric et al. (2007) extended Rastle et al.’s (2004) masked-priming design to the ERP domain. Using 42-ms primes preceded by forward masks and followed by targets that required lexical decision, they replicated Rastle et al.’s (2004) behavioral findings: significant and equivalent priming for transparent and opaque pairs, both of which yielded greater priming than non-morphological form pairs. Further, the amplitude of the N400 ERP component echoed the behavioral results: The N400 was more sensitive to priming in the transparent and opaque conditions than in the form condition (as indicated by the greater N400 attenuation in two of the four analyzed time windows in the

N400 range, 340–380 ms and 460–500 ms), with no detectable difference between the N400 effects in the transparent and opaque conditions. A shorter latency effect of priming (around 140–260 ms) had similar magnitudes in the three conditions, with more positive-going ERP amplitudes in response to targets preceded by related primes.

Using a similar masked priming lexical decision design, Morris et al. (2007) identified priming-sensitive ERP modulations of the same polarity and similar latency (early, 200–300 ms, and late, N400, 300–500 ms). There was no detectable effect of priming on the ERP in the nonmorphological form condition in either of these time ranges; in the transparent condition, priming was found in both ranges; in the opaque condition the effect of priming was reliable at 200–300 ms, but failed to reach significance in the N400 range (note, however, that the time window chosen for the N400 analysis, 300–500 ms, was likely to result in an underestimation of the N400 effect, which appeared to span the range between 400 and 600 ms following the target onset in the grand average ERPs). There was a significant linear trend both in the response times and ERPs (with the largest priming effect in the transparent condition and the smallest in the form condition, with opaque priming situated in the middle), which the authors interpreted as indicative of graded effects of semantic transparency. However, it is possible that the linear trend in Morris et al.’s (2007) study was a consequence of increased prime visibility as compared to Lavric et al.’s (2007) study. Whereas the latter used a prime duration and SOA of 42 ms, the former used a prime duration of 50 ms and an SOA of 70 ms. Behavioral investigations reveal that priming for opaque pairs falls away under these longer prime presentation conditions (Rastle et al., 2000). A subsequent study by Morris, Grainger, and Holcomb (2008), which used the same set of stimuli as in Morris et al. (2007) in a semantic categorization task, did not find a linear trend either at early latencies (<300 ms) or in the N400 range. Instead, both latency ranges seemed to reveal priming effects in the opaque condition when prime duration was 50 ms (SOA of 70 ms).

ERP Correlates of Long SOA Priming

ERP investigations of morphological priming have not been limited to masked-priming paradigms. The effects of semantic transparency have also been examined using fully visible primes (with longer SOAs and prime durations). Of particular relevance here are the studies by Barber, Dominguez, and de Vega (2002) and Dominguez, de Vega, and Barber (2004). As already mentioned, behavioral investigations using visible primes found no facilitatory effects in the opaque condition, whereas in the transparent condition fully visible primes led to robust priming (Rastle et al., 2000). Although this implicates semantic processing in the reduction/elimination of the priming seen in opaque pairs in conditions of masking, one cannot determine from the behavioral data alone at what point in the processing of the targets semantic information has its impact. Barber et al. used ERPs to address this issue. In a priming study in Spanish using an SOA of 250 ms, they found equal N400 reduction by priming in the transparent and opaque conditions (relative to their respective unrelated controls) up to the N400 peak, but subsequently N400 in the transparent condition remained attenuated, whereas in the opaque condition it appeared to rebound. These results suggest the early portion of the N400 time window as the time of the prime–target semantic integration, which reduces or eliminates priming in the opaque condition. Unfortunately, behavioral results were not reported by Barber et al. to show the latter was indeed the case. Moreover,

because of the lack of a nonmorphological form priming condition, one cannot rule out the possibility that the effects in the opaque condition were form driven.

These shortcomings were addressed by Dominguez et al. (2004), who used a similar paradigm and stimuli to those of Barber et al. (2002) and an SOA of 300 ms. Dominguez et al. found distinct effects of priming on ERPs associated with the opaque and form conditions. Whereas the effects of form priming on ERPs could not be distinguished from those of unrelated primes, the transparent and opaque conditions showed priming-related attenuation early in the N400 window, followed in the opaque condition by a negative wave peaking at 450–600 ms. Transparent, but not opaque, primes facilitated performance. Dominguez et al. interpreted the ERP negativity in the opaque condition as a delayed N400 (or a rebounded N400) resulting from the processing of the semantic incongruence between the prime and the target. However, careful inspection of the ERPs in the transparent and opaque conditions revealed a similar, albeit reduced, late negative wave at around 450–600 ms in the transparent condition whose interpretation is less clear.

The Present Study

The current study aims to document the ERP correlates of semantic transparency in morphological priming with fully visible primes in English, which to our knowledge has not yet been done. Furthermore, it seeks to examine long SOA priming in a set of transparent and opaque prime–target pairs, which showed similar behavioral and ERP priming in conditions of masked priming (Lavric et al., 2007). In the context of the long-SOA paradigm, the ERP technique may provide insights that are difficult to achieve exclusively with behavioral measures. In particular, it may be possible to assess whether morphological priming effects observed at long SOAs (e.g., *departure-DEPART*) are indeed morphological in nature or arise as a consequence of the semantic and form relationship characteristic of morphologically complex words and their stems (Rastle & Davis, 2008). Specifically, if at some point in the time course of target processing (e.g., in the early part of the N400 time range; see Barber et al., 2002; Dominguez et al., 2004), the transparent (e.g., *departure-DEPART*) and opaque (*corner-CORN*) conditions show ERP priming effects of comparable magnitude and greater than form priming (*brothel-BROTH*), this would suggest that long-SOA behavioral priming in the transparent condition is at least in part morphological. Such priming effects would be hard to explain by semantic or combined semantic and form overlap between primes and targets. First, because in the opaque condition primes and targets are not semantically related, any effect of semantics would be expected to be greater in (or limited to) the transparent condition. Second, there is no reason for a nonmorphological form overlap effect to manifest itself more strongly in the opaque condition than in the form condition.

Methods

Participants

Fourteen native English speakers (all students at the University of Exeter; 8 women, 6 men; mean age, 21.7 years; range, 18–29 years), were paid £10 for participating in the study. Participants, all of whom were right-handed (based on self-report), provided informed written consent before being tested. The study was approved by the local Ethics Committee (School of Psychology, University of Exeter).

Stimuli

The stimuli (see the Appendix) were 195 prime–target pairs that we employed previously in the context of masked priming (Lavric et al., 2007; we refer the reader to this paper for a full description of the stimulus statistics). Prime–target pairs were selected from the Celex English database (Baayen, Piepenbrock, & van Rijn, 1993). Sixty-six pairs were selected for the transparent and opaque conditions, and 63 pairs were selected for the form condition.¹ In the transparent condition, all primes were morphologically related to their targets, and this relationship was semantically transparent (e.g., *magical-MAGIC*). In the opaque condition, the prime–target pairs had an apparent morphological relationship, but were semantically unrelated (e.g., *compassion-COMPASS*). In the form condition, primes and targets overlapped orthographically, but had no semantic or (genuine or apparent) morphological relationship (e.g., *brothel-BROTH*). Form primes consisted of the target and an ending not used as an English suffix or used very infrequently as an English suffix (in no more than four orthographically transparent words such as *-n* in *silvern*). The majority of the transparent primes were derivations of their targets, and most of the opaque primes contained derivational (pseudo)suffixes. Related primes comprised 27 different suffixes in the transparent set and 30 suffixes in the opaque set.²

The targets from the form, opaque, and transparent conditions were closely matched for Celex frequency/million (36.22, 42.32, 48.10), length (4.76, 4.95, 5.00), and neighborhood size (2.38, 1.82, 1.9), respectively; the primes were matched for frequency (20.11, 44.52, 20.68); and the prime–target pairs were matched for orthographic overlap (0.67, 0.68, 0.69). Statistical analyses of the item set found that differences between conditions did not approach significance in any of the above measures (see Lavric et al., 2007). The three conditions were differentiated from one another with respect to prime–target semantic relatedness (Latent Semantic Analysis [LSA]; Landauer & Dumais, 1997): LSA similarity within the related prime–target pairs was much higher in the transparent condition than the form and opaque conditions, whereas the latter two conditions could not be distinguished statistically (see Lavric et al., 2007). For each target, suffixed control primes were selected, which were semantically, orthographically, and morphologically unrelated to targets, and were matched to related primes on frequency and length. In addition, 264 nonword targets (matched to word targets for length) were presented preceded by orthographically unrelated suffixed English word primes. To limit the predictability of the lexicality of the targets from the prime–target relatedness (all nonword targets had unrelated primes), the overall relatedness of word targets and their primes was reduced to about 37% by adding 66 filler word targets all preceded by unrelated primes.

¹Shortly before testing started, it was found that three items from the original set of 66 form items were incorrectly classified as nonmorphological (e.g., *textile-TEXT*); their removal (from the present study and from that of Lavric et al., 2007) resulted in the form set having three fewer prime–target pairs than the sets for the other two conditions.

²Two suffixes had the highest occurrence in both the transparent and opaque sets: *-er* was part of 10 primes in each condition and *-y* was contained by 9 primes in each condition. The remaining suffixes contained by the related primes were as follows: transparent, *-ly* (6 primes), *-ed* (4), *-age* (3), *-ic* (3), *-ing* (3), *-able* (2), *-al* (2), *-ary* (2), *-en* (2), *-et* (2), *-ion* (2), *-ment* (2), *-ry* (2), *-ard* (1), *-ate* (1), *-ee* (1), *-ern* (1), *-ery* (1), *-ful* (1), *-ial* (1), *-ise* (1), *-le* (1), *-less* (1), *-ory* (1), *-ous* (1); opaque, *-et* (6), *-ion* (4), *-ed* (3), *-al* (2), *-ary* (2), *-at* (2), *-ic* (2), *-ing* (2), *-ment* (2), *-ory* (2), *-ry* (2), *-ty* (2), *-able* (1), *-age* (1), *-ance* (1), *-ard* (1), *-ate* (1), *-cy* (1), *-en* (1), *-eous* (1), *-ern* (1), *-ery* (1), *-ey* (1), *-ious* (1), *-ise* (1), *-ity* (1), *-le* (1), *-less* (1).

Two stimulus lists, each containing all experimental targets, were made in order to counterbalance the assignment of related and unrelated primes to their respective targets over participants.³ Each list also contained all the nonword target pairs and all the unrelated filler pairs.

Procedure

Prime–target pairs were presented in randomized order for each participant using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Letter strings subtended a visual angle of 2.25–3.27° horizontally and 0.49–0.65° vertically. Each trial started with the presentation of a fixation cross for 500 ms, followed by the prime presented in lower case for 226 ms (17 refreshes of a CRT monitor at a refresh rate of 75 Hz), which in turn was followed by the target presented in upper case until a response was made. The stimuli and the fixation cross were displayed in black color against a white background. Participants were instructed to make a word/nonword response to the target by pressing a key with their right- or left-hand index finger, respectively (because only responses to words were analyzed, the response hand was not counterbalanced). Following the target, there was a feedback message (“Error”) displayed for 2040 ms if an error was made; otherwise the screen was blank for 2040 ms, after which the fixation for the next trial was presented. Forty practice trials using pairs not included either in the main stimulus set were run before testing started.

Electroencephalogram (EEG) Acquisition

The EEG was acquired with 64 Ag/AgCl electrodes, embedded in an elastic cap (ElectroCap International, Eaton, OH), and connected to BrainAmpMR amplifiers (Brain Products, Munich, Germany). Fifty-eight electrodes were placed on the scalp in a standard 10–10 configuration, two on the outer canthi of the eyes, two above and below the orbit of each eye, and two on the earlobes. The EEG cap placement was optimized with a CMS-20EP ultrasound digitizer (Zebris Medical, Isny, Germany). Prior to EEG data acquisition, it was ensured that electrode impedances did not exceed 5 kΩ. The EEG was sampled at 500 Hz with a bandpass of 0.016–100 Hz (reference, Cz; ground, AFz). Off-line, the EEG was low-pass filtered (30 Hz; 24 dB/oct) and re-referenced to the averaged earlobes.

Behavioral Analysis

Analyses of response times (RTs) and error rates were run both by subjects and by items using Priming (unrelated, related) × Condition (transparent, opaque, form) analyses of variance (ANOVAs) and (if necessary) subsequent *t* tests. The Huynh–Feldt correction for violations of sphericity was applied in ANOVAs where necessary; corrected significance levels and uncorrected degrees of freedom are reported.

ERP Analysis

The EEG was segmented into 800-ms-long ERP epochs time-locked to the onset of primes (plus a 100-ms pre-prime baseline). Epochs containing eye, muscle, and other artifacts and those associated with lexical decision errors were removed from the subsequent analyses. This left a mean of 30.2 epochs in the transparent condition, averaged over the related and unrelated

trials ($SD = 2.36$), 29.1 epochs in the opaque condition ($SD = 2.47$), and 26.4 segments in the form condition ($SD = 3.26$), which represented 91% ($SD = 7\%$), 88% ($SD = 7\%$), and 84% ($SD = 10\%$) of the total number of trials in each condition, respectively. (Note the higher overall error rate in the form condition; see Table 1.) The present hypotheses required an optimal balance of detailed temporal analysis of the time course of N400 (multiple tests with some cost to sensitivity due to the correction for inflation of Type 1 error) and more targeted tests that maximize sensitivity to subtle effects (statistical power). Our two-stage analysis, centered on N400 in response to targets (300–500 ms after target onset), attempted to address this balance.

In Stage 1, the detailed temporal and spatial characteristics of the N400 modulation by priming were obtained by averaging ERPs in 20 time bins of 10 ms spanning the N400 range and running *t* tests for each bin and scalp electrode on the ERPs for targets preceded by related versus unrelated primes. To control for the inflation of Type 1 error in multiple comparisons, the significance level of the resulting *t* statistic values were determined by means of permutations—a nonparametric procedure that does not assume normally distributed data (Nichols & Holmes, 2002). The permutations were run separately for each morphology condition (transparent, opaque, form). In each permutation, (1) one or more subjects’ ERPs were randomly re-assigned to the alternative prime type (i.e., the ERPs for the related primes were swapped with those for the unrelated primes for all electrodes and time bins); (2) the paired-samples *t* statistic, comparing the randomly swapped related and unrelated ERPs, was computed for each electrode and time bin and the highest *t* value (ignoring sign) retained. Ordering the *t* values resulting from permutations in decreasing order of magnitude enables one to determine the significance cutoff for a probability level of choice. For example, if a *t* value computed on the basis of observed (correctly labeled, nonpermuted) data is within the top 5% of the *t* values obtained with permuted data, the former is significant at .05 or less. For the present data, the total number of permutations (possible ways of labeling 14 subjects’ data as related or unrelated) was 2^{14} , or 16,384. By covering the entire set, we were able to determine the exact significance levels. As stated above, the complete set of permutations was run three times—once for each morphology condition. This means that, with respect to the probability of Type 1 error, the 1,160 tests contrasting amplitudes in related versus unrelated trials at 58 Electrodes × 20 Time Bins were equivalent to one test per morphology condition, that is, to a total of three uncorrected *t* tests.

In Stage 2, the potential temporal modulation of the Priming × Morphology interaction was first examined by submitting the ERP data (averaged in intervals determined in Stage 1 analyses) to an ANOVA that included factors morphology (3, transparent, opaque, form) and prime (2, related, unrelated). The Huynh–

Table 1. Mean RT (in Millisecond) and Error Rate (%) to Targets and the Priming Effect for Each of the Two Measures

	Condition					
	Transparent		Opaque		Form	
	RT	Errors	RT	Errors	RT	Errors
Related prime	663	1.9	717	5.8	805	9.1
Unrelated prime	754	4.1	761	9.3	807	13.2
Priming effect	91	2.2	44	3.5	2	4.1

³For the form condition, which comprised 63 pairs, this meant that half of the participants were presented with 31 related and 32 unrelated prime–target pairs and the other half with 32 related and 31 unrelated pairs.

Feldt correction for violations of sphericity was used in the ANOVA where necessary (corrected significance levels and uncorrected degrees of freedom are reported). Subsequently, the magnitude of the priming N400 effect was compared across conditions (transparent, opaque, form) by means of *t* tests on the control-minus-related ERP difference. To maximize sensitivity (statistical power), the number of tests was limited by (1) running the tests only in a limited number of electrodes where the N400 effect was most consistent and (2) averaging the ERPs over the time bins from Stage 1 (the exact time ranges for averaging were decided on the basis of the time bins with robust priming in Stage 1). As in Stage 1, statistical significance was determined by means of permutations. The 16,384 permutations were run only for the selected electrodes and time ranges, separately for three contrasts (transparent vs. form, opaque vs. form, and transparent vs. opaque), thus reducing the probability of Type I error to that of three uncorrected tests.

Results

Behavioral Results

The analyses of RT revealed a main effect of priming, $F_1(1,13) = 19.42$, $p = .001$; $F_2(1,192) = 25.99$, $p < .001$ (the subscripts refer to the by-subjects and by-items analyses, respectively), as well as a reliable priming by morphology interaction, $F_1(2,26) = 15.2$, $p < .001$; $F_2(2,192) = 6.36$, $p = .002$. Follow-up tests revealed reliable effects of priming (faster responses to the targets preceded by related primes relative than to targets preceded by unrelated primes; see Table 1) in the transparent, $t_1(13) = 9.08$, $p < .001$; $t_2(65) = 5.79$, $p < .001$, and opaque conditions, $t_1(13) = 2.98$, $p = .01$; $t_2(65) = 2.92$, $p = .005$, but no such effect in the form condition, $t_1(13) = 0.76$, $p = .94$; $t_2(62) = 0.52$, $p = .61$. The priming effect was significantly greater in the transparent condition than in the opaque, $t_1(13) = 4.11$, $p = .001$; $t_2(130) = 2.24$, $p = .027$, and form, $t_1(13) = 5.26$, $p < .001$; $t_2(127) = 3.4$, $p < .001$, conditions, whereas the difference between the latter two conditions failed to reach significance by items, $t_1(13) = 2.21$, $p = .046$; $t_2(127) = 1.43$, $p = .15$.

The analyses of error rates revealed a main effect of priming, $F_1(1,13) = 11.86$, $p < .01$; $F_2(1,192) = 13.2$, $p < .001$, but no interaction between priming and condition ($ps > .40$).

ERP Results

Stage 1: Priming within conditions. The electrode-wise contrasts run for each of the 20 time bins in the range of the N400 component (300–500 ms after target onset) found reliable effects of priming already in the earliest time bins (see Figure 1 and Table 2). N400 amplitude was reduced in response to targets preceded by related primes as compared to those preceded by unrelated primes (see Figure 1A,B), an effect that was statistically significant in some electrodes in the transparent and opaque conditions as early as 300–330 ms (see Figure 1C).⁴ In both of

these conditions, the related versus unrelated N400 difference steadily increased in magnitude and spatial extent until about 370–380 ms, whereas in the form condition the effect of priming on N400 was first reliably detected only in the 10th time bin (starting at 390 ms; see Figure 1C). From ~380 ms, the ERPs associated with related and unrelated priming diverged further in the transparent condition, whereas in the opaque condition this difference started to reduce to the amplitude and spatial extent observed in the form condition (see Figure 1B,C).

Stage 2: Comparing the magnitude of priming across conditions. Stage 1 analyses suggested a biphasic time course of priming. During the first ~70–80 ms of the analyzed range, the attenuation of N400 in the opaque condition mirrored the N400 effect observed in the transparent condition (see Figure 1B,C). From ~380 ms after target onset, this N400 priming effect increased further in the transparent condition, persisting until ~480 ms, whereas in the opaque condition it eventually faded to the level seen in the form condition. In Stage 2, two equal and contiguous 80-ms-long time windows were defined in accordance with the above time course (300–379 ms and 380–459 ms) with the aim of running electrode-wise contrasts comparing pairs of conditions in the magnitude of this priming effect. To maximize power in multiple tests, only electrodes that showed the most consistent priming in Stage 1 (at least half of the temporal range, i.e., ≥ 10 bins, in any morphological condition) were selected for Stage 2 analyses. Of the 14 electrodes that met this criterion based on Stage 1 priming (F4, FC3, FC1, FCz, FC2, FC4, CP5, CP3, CP1, P3, P1, Cz, CP2, CP6), 12 did so in the transparent condition (F4, FC3, FC1, FCz, FC2, FC4, CP5, CP3, CP1, P3, P1, Cz), and 3 in the opaque condition (FC4, CP2, CP6; see Table 2).⁵

Prior to running the electrode-wise contrasts, we assessed the temporal modulation of the Priming \times Condition interaction in an ANOVA with factors time window (2), prime (2), morphology (3), and electrode (14). The reliable main effect of prime, $F(1,13) = 82.73$, $p < .001$, reflected a substantial attenuation of the N400 for targets preceded by related primes. The critical interactions testing the biphasic pattern of priming suggested by Stage 1 analysis were also significant: Time Window \times Prime \times Morphology, $F(2,26) = 8.60$, $p = .001$; Time Window \times Prime \times Morphology \times Electrode, $F(26,338) = 3.38$, $p = .001$.⁶

⁵Although no electrodes in the form condition came close to showing ≥ 10 bins of statistically reliable priming in Stage 1, two of the selected electrodes revealed form priming in Stage 1 including Cz—the electrode that showed the most consistent priming in the form condition. One may wonder whether our selection criterion, which was only met in the transparent and opaque conditions, biased the Stage 2 contrasts away from finding greater priming in the form than the other conditions. However, in all the electrodes that showed reliable form priming in Stage 1, the related–unrelated difference (computed either in 10-ms bins as in Stage 1 or in 80-ms bins as in Stage 2) was always numerically smaller in the form condition than the other two conditions. This effectively means that there could not be greater form priming than transparent or opaque priming in Stage 2 contrasts whatever the electrode selection.

⁶Both of these interactions were also highly reliable in a whole-head ANOVA run on voltages averaged in five regions on the left: anterior frontal (Fp1, AF3, F1, F3, F5, F7), frontal-central (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, Time Window \times Prime \times Morphology, $F(2,26) = 8.69$, $p = .009$; Time Window \times Prime \times Morphology \times Scalp Region, $F(8,104) = 11.27$, $p < .001$.

⁴The presence of reliable priming in the first time bin of the analyzed range (in the opaque condition) left open the possibility that the priming effects started considerably earlier than the analysis interval. To examine this possibility, we also ran the Stage 1 analysis on an extended interval (240–500 ms), which showed that the priming seen in two electrodes at 300 ms in the opaque condition started at 280 ms. Because no other or earlier effects were found and because a longer analysis interval exacerbates the severity of the multiple comparisons problem, the subsequent analyses were conducted in the original interval of 300–500 ms.

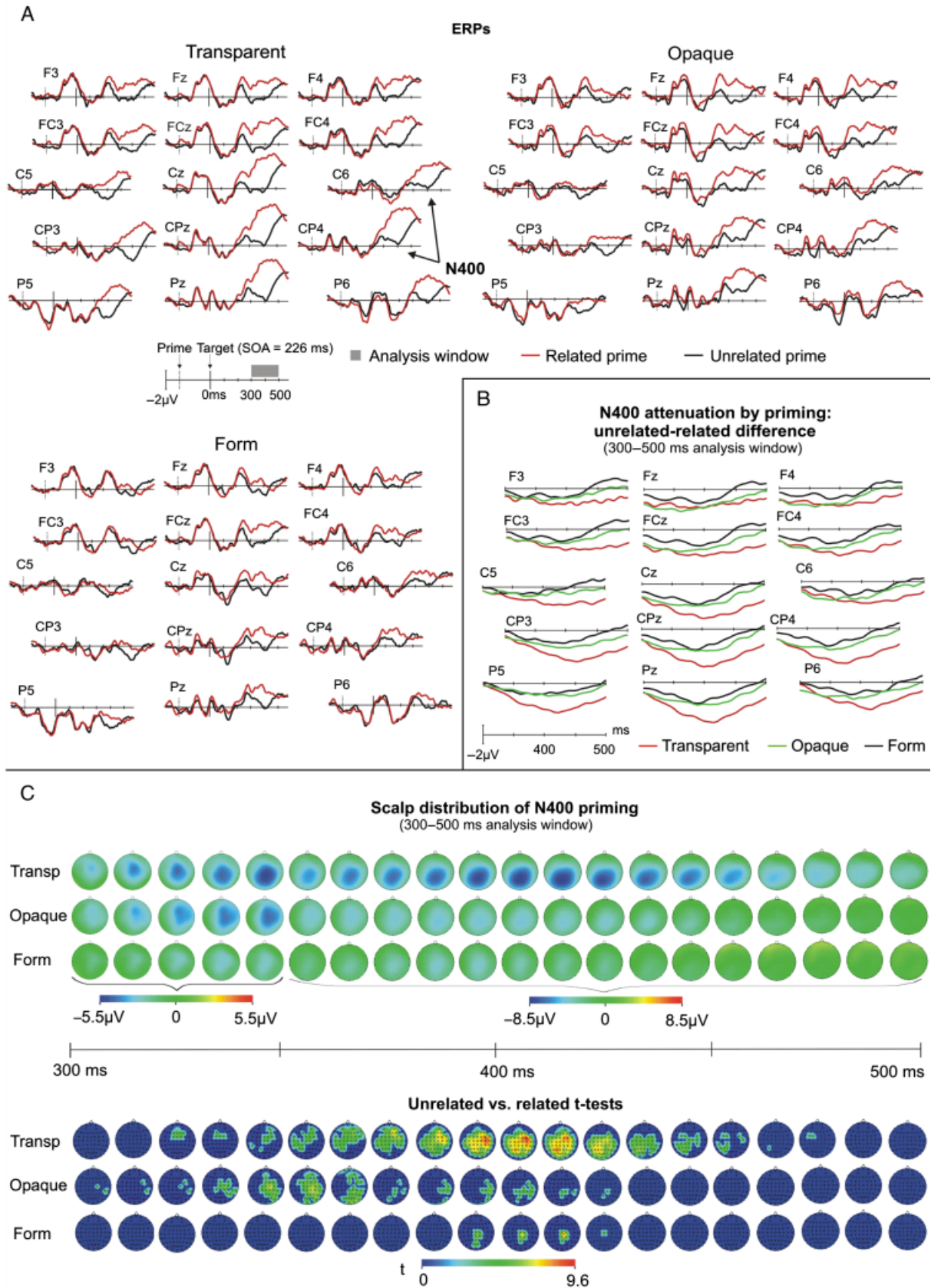


Figure 1. A: ERP waveforms in 15 representative electrodes. B: Difference waves in the N400 (300–500 ms) range. C: Detailed spline-interpolated maps of the unrelated-minus-related difference in N400 and linearly interpolated maps of statistically significant electrode- and bin-wise t tests (each map represents a 10-ms time bin; small black circles on the t maps represent scalp electrodes). Note the similar N400 attenuation by priming in the first 70–80 ms of the analysis window in the transparent and opaque conditions, followed by greater priming in the transparent condition from about 380 ms onward.

Table 2. Summary of Stage 1 Tests Including the Electrodes That Showed Significant Related versus Unrelated Differences in Each Time Bin and for Each Morphology Condition, as well as the Associated Ranges of *t* and *p* Values^a

Time bin (ms)	Transparent				Opaque				Form	
	Electrode	<i>t</i> range	<i>p</i> range	Electrode	<i>t</i> range	<i>p</i> range	Electrode	<i>t</i> range	<i>p</i> range	
300–309				C2, CP6	5.4, 5.91	.027, .015				
310–319				FC4, CP6	5.07, 6.0	.041, .013				
320–329	F1, Fz, F2, F4, FC1, Fz, FC2	4.85–5.81	.039–.009	FC4, C2, CP6	4.99–5.52	.045–.023				
330–339	F1, FC1, Fz, FC2	4.74–5.08	.047–.026	FCz, FC4, C2, C4, CP1, CP2, CP6, TP8, P4, P6, Cz	5.11–6.5	.039–.008				
340–349	AF4, F4, Fz, FC2, FC4, C2, CP5, P1, Cz	4.71–5.28	.049–.02	Fz, FCz, FC2, FC4, C1, C2, C4, CP1, CPz, CP2, CP4, CP6, Pz, P2, P4, P6, PO4, PO8, Cz	5.0–7.47	.045–.002				
350–359	AF4, F1, F2, F4, FC5, Fz, FC2, FC4, C5, C3, C2, CP5, CP3, CP1, P3, P1, Cz	4.8–6.18	.042–.005	AF4, Fz, F4, FC3, FC1, FCz, FC2, FC4, C1, C2, C4, C6, CP1, CPz, CP2, CP4, CP6, Pz, P2, P4, P6, PO1, POz, PO4, PO8, Oz, Cz	4.92–6.96	.05–.004				
360–369	AF3, AF4, F1, Fz, F2, F4, F8, FC5, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, CP5, CP3, CP1, P3, P1, Cz	4.8–6.25	.042–.005	Fp1, AF4, Fz, F4, FCz, FC4, FC6, C2, CPz, CP2, CP4, CP6, Pz, P2, P4, PO1, POz, PO2, PO4, PO8, Oz, O2	4.92–6.47	.05–.008				
370–379	AF3, AF4, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP4, CP6, P3, P1, Pz, POz, Cz	4.73–8.2	.048–.001	FC4, CP2, CP6, P2, PO1, POz	5.01–5.86	.044–.016				
380–389	AF4, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P3, P1, Pz, POz, Cz	4.81–7.99	.042–.001	FC4, C6, CP2, CP4, CP6, PO8	5.09–6.12	.041–.012				
390–399	F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P3, P1, Pz, P2, P4, P6, PO3, PO1, POz, PO2, PO4, O2, Cz	4.9–8.87	.036–.0004	FC4, C6, CP2, CP4, CP6, P6, PO8	4.92–7.1	.05–.004	C2, CPz, CP2, Pz, PO1, POz, PO2, Cz	5.18–6.34	.05–.011	
400–409	F1, Fz, F2, F4, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, P6, PO3, PO1, POz, PO2, PO4, O2, Cz	4.71–9.59	.049–.0002	FC4, C2, C6, CP1, CPz, CP2, CP4, CP6, Pz, P6, PO1	4.93–5.96	.049–.014	C2, CPz, CP2, Pz, Cz	6.24–7.14	.012–.003	
410–419	AF4, F1, Fz, F2, F4, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, P6, PO3, PO1, POz, PO2, PO4, O1, O2, Oz, Cz	4.82–8.74	.041–.0004	CPz, CP2, CP6, Pz	5.04–5.5	.043–.024	C2, CPz, CP2, Pz, Cz	5.82–8.83	.021–.001	
420–429	F4, FC3, FC1, FCz, FC2, FC4, C5, C3, C1, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, P6, PO7, PO3, CP1, CPz, PO7, PO3, PO1, POz, PO4, Cz	4.81–7.75	.042–.001	CP2, Pz	4.95, 5.1	.048, .039	Cz	5.68	.026	
430–439	FC3, FC1, FC2, FC4, C5, C3, C1, C2, C4, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P4, P6, PO7, PO3, PO1, POz, PO4, Cz	4.73–6.62	.048–.003							
440–449	FC3, FC1, FC4, C2, C4, CP5, CP3, CP1, CPz, CP4, P5, P3, P1, Pz, PO3, PO1, Cz	4.77–5.68	.044–.011							
450–459	FC3, FC1, FC4, C6, CP5, CP1, P5, P3, P1, PO3	4.83	.041							
460–469	P3	4.808,	.0419, .04							
470–479	FC3, FC1	4.809	.17							
480–489										
490–499										

Note: The electrodes that were selected for Stage 2 (significant in 10 or more time bins) are shown in bold font: 12 in the transparent condition (selected for the transparent vs. form and transparent vs. opaque contrasts in Stage 2) and 3 in the opaque condition (selected for the opaque vs. form and transparent vs. opaque contrasts in Stage 2).

The temporal pattern of differences between conditions in priming magnitude was further detailed by means of permutation-corrected contrasts run on the related-minus-unrelated difference in individual electrodes. The transparent versus form contrast (greater N400 attenuation in the transparent condition), conducted in the 12 electrodes that met the selection criterion in the transparent condition in Stage 1 (see above), survived correction in the left-parietal electrode CP5 in the 300–379 ms time window, $t(13) = 3.27$, $p = .048$, and in this plus nine other electrodes in the 380–459 ms time window (F4, FC3, FC2, FC4, CP5, CP3, CP1, P3, P1, Cz), $3.35 \leq t(13) \leq 5.95$, $.0002 \leq p \leq .041$. The opaque versus form contrast (greater opaque than form priming), conducted in the three electrodes that met the selection criterion, was reliable in the right parietal electrode CP6 in the 300–379 ms time window, $t(13) = 2.9$, $p = .048$; no reliable opaque versus form differences were found in the subsequent time window (380–459 ms). The transparent versus opaque conditions did not reliably diverge in any of the 14 selected electrodes between 300 and 379 ms (even uncorrected, p s were $> .2$), whereas in the 380–459 ms time window two left-parietal electrodes showed significantly greater priming in the transparent condition than in the opaque condition: P1, $t(13) = 3.45$, $p = .047$; P3, $t(13) = 3.85$, $p = .024$.

Stage 2 analyses confirmed the temporal dynamics of priming suggested by Stage 1 tests. The transparent condition was associated with greater magnitude of priming than the form condition throughout the analysis interval, with this difference increasing in the late part of the interval. In contrast, evidence of greater opaque than form priming was only found in the early time window (300–379 ms), during which opaque priming was indistinguishable from transparent priming; in the late part of the interval (380–459 ms) the opaque condition showed similar priming to the form condition and less priming than the transparent condition.

Discussion

The present study examined the role of the semantic relationship between morphologically complex words (*replay*) and their stems (*play*) in the decomposition of the former into their constituent morphemes ($\{\text{re-}\} + \{\text{play}\}$). Our theoretical objective was to make sense of two seemingly inconsistent bodies of data. On the one hand, behavioral (e.g., Longtin et al., 2003; Rastle et al., 2004; see Rastle & Davis, 2008, for a review) and neurophysiological (e.g., Lavric et al., 2007) masked-priming studies have suggested that the semantic relationship between morphologically complex words and their stems is irrelevant as far as decomposition is concerned. Significant and equivalent masked-priming effects are obtained for prime–target pairs with a semantically transparent (e.g., *darkness-DARK*) and semantically opaque relationship (e.g., *corner-CORN*), with both yielding greater priming effects than prime–target pairs with a nonmorphological form relationship. On the other hand, data from paradigms in which primes are available to conscious perception have suggested that the semantic relationship between morphologically complex forms and their stems is a critical factor in determining whether those complex forms are decomposed: priming effects are observed when prime–target pairs have a semantically transparent relationship but not when they have a semantically opaque relationship (Longtin et al., 2003; Rastle et al., 2000; see also Meunier & Longtin, 2007). Though it is now

reasonably well accepted that the masked priming data implicate a rapid form of decomposition that is blind to semantic information (Rastle & Davis, 2008), precisely how to interpret data from the longer SOA paradigms remains controversial. Specifically, it is not known whether these data reflect (a) a second form of (semantically based) decomposition (e.g., Diependaele, Sandra, & Grainger, 2005), (b) a “licensing” procedure that cancels inappropriate decompositions on the basis of semantic information (Meunier & Longtin, 2007), or (c) an effect of pure semantic (e.g., *violin-cello*) or semantic plus orthographic (e.g., *brunch-lunch*) overlap (see Rastle & Davis, 2008).

We combined behavioral measures of priming with fully visible primes (SOA = 226 ms) with an analysis of the N400 brain potential. N400 has been previously associated with lexical and semantic processing, both in the context of single words (e.g., Brown & Hagoort, 1993; Holcomb, Reder, Misra, & Grainger, 2005; Kiefer, 2002) and sentences (e.g., van Berkum, Hagoort, & Braun, 1999; Weber & Lavric, 2008; see also Kutas & Federmeier, 2000, for a review); it has also been shown to be sensitive to morphological differences such as regular versus irregular inflections (see Lavric, Pizzagalli, Forstmeier, & Rippon, 2001, for a review). Behaviorally, the current results revealed substantially greater facilitation in the transparent condition than in the opaque and form conditions (see Table 1); the latter two were distinguished in the analysis by subjects but not by items. In one respect the present behavioral results depart from the previous long SOA priming data (e.g., Rastle et al., 2000): We found some facilitation in the opaque condition, whereas Rastle et al. (2000) reported for an almost identical SOA (230 ms) prime-induced inhibition in their opaque pairs. One aspect of the design that distinguishes the two studies is that some of Rastle et al.’s prime–target pairs were related in meaning, but not form (e.g., *violin-cello*), which was likely to draw attention to the semantic relationship between the prime and the target. In the present study, where there were no such pairs, the surface relationship prevailed (all related primes were orthographically related to the targets and only transparent primes were also semantically related to the targets), possibly resulting in less attention to the semantic relationship between the prime and the target. This being said, the two sets of results are in agreement in that there is greater priming-induced facilitation in the transparent pairs than in the opaque pairs. The key issue of interest to us was how this reduced behavioral facilitation in the opaque condition manifested itself neurophysiologically.

Detailed temporal analysis of the attenuation of the N400 component in response to targets preceded by related (as compared to unrelated) primes (see Figure 1A), identified two phases in the time course of priming in the opaque condition. Early in the N400 range (~ 300 – 380 ms), robust priming of equivalent magnitude and topography was observed in the opaque and transparent conditions; both were distinguishable from the form condition (see Figure 1B,C). This pattern of N400 priming is reminiscent of the N400 results we obtained previously with masked priming (Lavric et al., 2007; see Introduction). The second phase (from 380 ms onward), was characterized by a reversal or reduction of the N400 attenuation in the opaque condition until it eventually reached the level seen in the form condition, whereas N400 priming in the transparent condition continued to be robust (and greater than priming in the opaque and form conditions; see Figure 1B,C). This biphasic pattern of opaque priming we observed for English primes, which are derivations or pseudo-derivations of their targets, is highly consistent with the

N400 priming reported by Barber et al. (2002) and Dominguez et al. (2004) in their long-SOA investigations of inflections (transparent condition, e.g., *loca-LOCO*; madwoman-madman) and pseudo-inflections (opaque condition, e.g., *rata-RATO*; rat-moment) in Spanish (see Introduction). It is also consistent with a recent proposal that the N400 component may contain two subcomponents (Grainger & Holcomb, 2009): an early one that reflects the interactions between lexical and semantic processing and a following subcomponent sensitive to the processing of meaning beyond the word level. The priming effects we documented in the range between ~300 and 380 ms may reflect target-induced lexical and semantic activation that is insensitive to the semantic context created by the prime (thus mapping onto the early subcomponent in Grainger and Holcomb's characterization of N400 above), whereas the sensitivity to the semantic context created by the prime from 380 ms onward (as indicated by the greater priming in the transparent condition) may be a manifestation of the second subcomponent of N400.

The implication of the above pattern of long-SOA N400 priming for models of morphological processing is threefold. First, the equivalent magnitude of priming in the opaque and transparent conditions (both greater than form priming) early in the N400 range suggests that long-SOA behavioral priming in the transparent condition is unlikely to arise exclusively from semantic (or semantic and orthographic) overlap (as in *violin-cello* or *lunch-brunch*). Indeed, primes and targets in the opaque condition are not semantically related (e.g., *corner-CORN*). One therefore has to conclude that the behavioral long-SOA facilitation in pairs such as *darkness-DARK* is, at least in part, morphological. The alternative is to posit either that the observed ERP and behavioral priming effects are unrelated or that priming-related N400 effects with very similar time courses, magnitudes, and spatial distributions in the transparent and opaque conditions are caused by different processes. Neither of these assumptions seems plausible. Second, the fact that, as in our masked priming study (Lavric et al., 2007), semantic influences on priming in the early portion of the N400 range seem very limited or nonexistent points to a morphological decomposition mechanism that operates on orthographic input and is oblivious to semantic influences.

The third implication concerns the timing of the effect of semantic transparency on the observed pattern of N400 priming in the opaque condition. In all three ERP studies that compared

transparent and opaque long-SOA priming (the present study and those of Barber et al., 2002, and Dominguez et al., 2004) the opaque and transparent conditions started to diverge (which we take as a temporal index of the effect of semantic transparency) at ~380–450 ms following the onset of the target: ~606 ms after the onset of the prime in the present study, ~750 ms in Barber et al. (2002), and ~650 ms in Dominguez et al. (2004). This means that at 600 ms or later after the onset of the prime, the magnitude of priming observed in the opaque and transparent conditions was similar. Even allowing for sharing of resources for the processing of the prime and the target (though the SOAs of 226 ms, 250 ms, and 300 ms in the three studies allowed for much of the processing of the prime to take place before the target was presented), the onset of the effects of semantic transparency ~600–700 ms seems too late to reflect an obligatory semantically based decomposition stage that follows earlier, orthography-based decomposition. Instead, this time course of priming is more consistent with a single, orthography-based decomposition mechanism, which up to a point is equivalent in masked and long-SOA designs and which is “licensed” (Meunier & Longtin, 2007) by the semantic system depending on the availability of relevant semantic information (e.g., in long-SOA designs). The fact that the degree of suppression of priming in the opaque condition is greater with stimulus sets that include prime–target pairs related only in meaning (Rastle et al., 2000), possibly increasing attention to the semantic prime–target relationship, than in stimulus sets where form overlap prevails (the present design) is also consistent with a late, controlled, intervention by the semantic system.

In conclusion, the present study revealed two stages of neural priming with fully visible primes in English: an early stage at which the mere appearance of morphological structure fully accounts for the observed priming and a later stage at which semantic transparency is at play. These findings, consistent with the previously documented time course of long-SOA inflection-based priming in Spanish, show that behavioral priming detected long-SOA paradigms in the transparent condition cannot just be an effect of pure semantic (e.g., *violin-cello*) or semantic plus orthographic (e.g., *brunch-lunch*) overlap. The lateness of the effects of semantic transparency favors a single, orthography-based mechanism of morphological decomposition licensed at a late processing stage, over a two-mechanism (orthography-based plus semantically based) decomposition account.

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APPENDIX

Table A1. Word Stimuli (Excluding Fillers)

Target	Related prime	Unrelated prime
Transparent condition		
ACID	acidic	yearly
ACRE	acreage	plunder
ADOPT	adopted	kingdom
AGREE	agreement	equipment
ALARM	alarming	composer
ANGEL	angelic	watcher
ARTIST	artistry	calmness
AVOID	avoidable	wonderful
BARON	baronet	voucher
BEARD	bearded	thinker
BLOOD	bloody	active
BOMB	bomber	lessen
BULB	bulbous	finely
CHILL	chilly	leftist
CLOUD	cloudless	enactment
CREAM	creamy	watery
CRITIC	critical	tendency
DIET	dietary	wearily
DREAM	dreamer	masonry
DRUNK	drunkard	feathery
EMPLOY	employer	addition
ERUPT	eruption	swelling
FILTH	filthy	harden
FIZZ	fizzle	touchy
FLESH	fleshy	lovers
FLOAT	floater	missive
GLOOM	gloomy	millar
GOLF	golfer	thinly
GOVERN	government	situation
GREEN	greenery	snobbish
GUILT	guilty	formal
INHIBIT	inhibitory	amateurish
LEGEND	legendary	anxiously
MAGIC	magical	detailed
MARSH	marshy	thorny
MOURN	mourner	tripper

Table A1. (Contd.)

Target	Related prime	Unrelated prime
NORTH	northern	friendly
NYMPH	nymphet	acutely
OXYGEN	oxygenate	fossilise
POET	poetry	dealer
PRISON	prisoner	bitterly
QUIET	quieten	mimicry
REACT	reaction	physical
RENEW	renewable	exemption
RHYTHM	rhythmic	abruptly
RISK	risky	downs
SCALD	scalding	jauntily
SILENT	silently	awfully
SMOOTH	smoothly	reflection
SOFT	soften	heroic
SWIFT	swiftly	foolish
TEACH	teacher	finally
TEETH	teething	warning
TIMID	timidly	flourish
TOAST	toaster	wishful
TRAIN	trainee	cookery
TUFT	tufted	silken
TUTOR	tutorial	strictly
VAGUE	vaguely	classic
VICAR	vicarage	presently
VIEW	viewer	ranger
VIVID	vividly	drawer
VOCAL	vocalise	wealthy
WIDOW	widowed	beastly
WRECK	wreckage	normally
YOUTH	youthful	performer
Opaque condition		
ACCESS	accessory	motoring
AMEN	amenable	palpably
AMP	ample	widen
APART	apartment	synonymous
ARCH	archer	feudal
AUDIT	audition	selfless

Table A1. (Contd.)

Target	Related prime	Unrelated prime
AUTHOR	authorise	strangely
BOARD	boarder	factual
BRAND	brandy	safely
BRISK	brisket	foundry
BUZZ	buzzard	loyally
CASUAL	casualty	flushed
COAST	coaster	muffler
COMPASS	compassion	blackness
COUNT	country	service
COURT	courteous	developer
CRAFT	crafty	vainly
CROOK	crooked	pottery
CRYPT	cryptic	dweller
DEPART	department	production
DISC	discern	starter
EARL	early	within
EMERGE	emergency	advertise
EVENT	eventual	grocery
FACET	facetious	distantly
FLEET	fleeting	simplify
FLICK	flicker	advisor
FRUIT	fruitless	alcoholic
GLOSS	glossary	sufferer
GLUT	gluten	bridal
GRUEL	grueling	existent
HABIT	habitat	cheering
HEART	hearty	folder
HELM	helmet	eighty
IMPORT	importance	grinder
INFANT	infantry	validity
INVENT	inventory	murderous
IRON	irony	sandy
LIQUID	liquidate	extremism
NUMB	number	really
ORGAN	organic	leaflet
PLAN	planet	editor
PLUCK	plucky	winger
PLUM	plumage	broiler
PRIOR	priory	digital
PROPER	property	stationery
PUTT	putty	fishy
QUEST	question	actually
RATION	rational	steadily
RECESS	recession	guarded
SCULL	scullery	narrowly
SECRET	secretary	obviously
SIGN	signet	frosty
SNIP	sniper	hourly
SPLINT	splinter	idealism
STILT	stilted	gaseous
STREAM	streamer	bashful
SWEAT	sweater	tattered
THICK	thicket	scruffy
TREAT	treaty	angler
TROLL	trolley	naughty
TRUMP	trumpet	chatter
UNIT	united	others
VITAL	vitality	orbital
WHISK	whisker	coyness
WOMB	wombat	sweetly
Form condition		
APPEND	appendix	believer
ARSE	arsenal	bonded
BASIL	basilica	princely
BROTH	brothel	warfare
BUTT	button	prayer
CANDID	candidacy	epileptic
CHAMP	champagne	stylistic
CHANCE	chancellor	meeting
COLON	colonel	ability
COMMA	command	eviction

Table A1. (Contd.)

Target	Related prime	Unrelated prime
DEMON	demonstrate	instruction
DIAL	dialog	lately
ELECT	electron	suburban
ETHER	ethereal	rumbling
EXTRA	extract	justify
FORCE	forceps	prudish
FORGE	forget	granary
FREE	freeze	golden
FUSE	fuselage	citation
GALA	galaxy	keeper
GLAD	glade	cuffs
HEAVE	heaven	firmly
INFER	inferno	frilled
INTERN	international	revolutionary
JERK	jerkin	twisty
MARINA	marinade	ordering
OPERA	operate	naturally
PARENT	parenthesis	lectureship
PHONE	phonetic	dreadful
PLAIN	plaintiff	absurdity
PLEAT	pleat	rocket
PLUS	plush	filmy
PULP	pulpit	gifted
QUART	quartz	roller
RABBI	rabbit	weekly
ROMAN	romance	searching
SALMON	salmonella	petulantly
SCRAP	scrape	ninety
SEMI	seminar	customs
SHOVE	shovel	tricky
SHUN	shunt	itchy
SIGH	sight	happy
SMUG	smuggle	twelfth
SOLID	solidarity	adventure
SOMBRE	sombrero	taunting
SQUAW	squawk	oddy
STAMP	stampede	defector
STIR	stirrup	buoyant
STUB	stubborn	moisture
STUD	studio	gently
STUN	stunt	misty
SURF	surface	medical
SURGE	surgeon	novelty
TABLE	tablet	singing
TAXI	taxidermy	numerical
TEMPER	temperature	affection
TRAMP	trampoline	symbolise
TWIN	twinkle	cheaply
TWIT	twitch	lesser
VILLA	villain	grossly
VIOLA	violation	stringent
WEIR	weird	manly
WINCE	winceyette	foreigner