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Semantic transparency and masked morphological priming: An ERP investigation

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Abstract

The role of semantics in the segmentation of morphologically complex words was examined using event-related potentials (ERPs) recorded to target words primed by semantically transparent (hunter–hunt,) opaque (corner–corn), and orthographically related (scandal–scan) masked primes. Behavioral data showed that only transparent items gave rise to priming. The ERP data showed both N250 and the N400 effects with transparent items generating greater priming than orthographic or opaque. Furthermore, priming effects across conditions revealed the existence of a significant linear trend, with transparent items showing the greatest effects and orthographic items the smallest, suggesting that these priming effects vary as a function of morphological structure and semantic transparency. The results are discussed in terms of a model of morphological processing.

Descriptors

ERP; N400; Masked priming; Morphology

Prior research on the processing of morphologically complex words has focused on identifying the extent to which morphological information is automatically retrieved during word processing. Most researchers agree that morphological information of some kind becomes available during the processing of a complex word. Nevertheless, there is still disagreement about how this information is stored in memory. Complex words may be stored as full forms in the mental lexicon or, alternatively, they may be represented as a combination of their constituent morphemes and undergo decomposition during processing.

The degree to which morphologically complex words are semantically transparent may be important in determining to what extent such words undergo decomposition, as it seems intuitively plausible that lexical entries for semantically related words should be related in some way (Marslen-Wilson, Tyler, Waksler, & Older, 1994). If semantically related items share the lexical entry of their common stem, it is possible that lexical access is achieved via a representation of the stem rather than the derived form. A morphologically complex word is semantically transparent if its meaning can be derived directly from the combined meaning of its stem and affix (e.g., "un-happy"). In contrast, the meaning of semantically opaque words

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(e.g., "department") cannot be directly derived from the combined meaning of their component morphemes. Although at an earlier time in the history of the English language such words may have been related, and they may still be considered to have a morphological structure in that they consist of a clear stem and affix, the morphological relationship is formal rather than semantic.

The present study aims to provide further empirical evidence with respect to the extent to which morphologically complex words are decomposed during processing, by using morphological priming and event-related potential (ERP) recordings.

Morphological Priming

Studies that have used an immediate priming paradigm with long stimulus onset asynchronies (SOAs) or those that have used delayed priming in which unrelated items intervene between prime and target have shown that the presentation of a morphologically related prime facilitates target processing (e.g, "hunter" followed by "HUNT") (Fowler, Napps, & Feldman, 1985; Stanners, Neiser, Hernon, & Hall, 1979). In addition, these studies have shown that morphological priming can be distinguished from purely orthographic and semantic priming in that morphological priming produces stronger and longer lasting facilitation than does semantic priming, whereas orthographic priming tends to result in inhibition (Drews & Zwitserlood, 1995; Feldman, 2000).

Unfortunately, the results of behavioral studies using immediate priming with long SOAs, or delayed priming, can be difficult to interpret because it is unclear whether the priming effects observed are the result of automatic lexical processes (e.g., activation of a lexical entry) or the result of an episodic memory of the prime influencing the decision process to the later target. These studies are also vulnerable to the use of predictive strategies by participants if the relationship between prime–target pairs becomes obvious. These concerns can be partially addressed with the use of the masked priming paradigm of Forster and Davis (1984). In this paradigm, a prime is visually presented very briefly for a period of approximately 50 ms. The prime is masked by the prior presentation of amasking stimulus, typically a series of hash marks (#####) or random consonant strings (SDFGHJK). The prime is either immediately followed by another mask or by the target, which serves as a backward mask. The short prime duration, as well as the presence of the forward and backward masks, prevents the subject from consciously perceiving the prime. Thus, any effects of the prime on responses to the target are presumed to reflect automatic rather than strategic processes or the effects of episodic memory.

Using the masked priming paradigm Grainger, Colé, and Segui (1991) found that primes that are morphologically related to target words facilitate target processing in the lexical decision task. Prefixed and suffixed target words were primed equally well by their stems (e.g., hunt–HUNTER) and other derived words with the same stem (hunter–HUNTING). Most important, morphological priming was robust when measured against orthographic controls (items such as "SCANDAL–scan," which share a similar degree of letter overlap between the prime and target but which do not share a common morpheme). This suggests that the effects of morphology in visual word recognition cannot be reduced to the effects of orthographic structure. One central goal in recent research on word recognition has been to distinguish morphological priming effects from orthographic priming on the one hand and semantic priming on the other, with the aim to specify the relative contribution of these different types of representation.

In a seminal study, Rastle, Davis, Marslen-Wilson, and Tyler (2000) used a masked priming procedure with three prime exposure durations (43, 72, and 250ms) to examine morphological, semantic, and orthographic priming. They found that morphologically related, semantically transparent primes (e.g., hunter–HUNT) were as effective as identity primes (hunt–HUNT) at all SOAs. These effects were greater than those found for purely semantically related (e.g., cello–VIOLIN) or purely orthographically related (e.g., electrode–ELECT) primes. They also found priming for semantically opaque, morphologically related primes at the shortest SOA (e.g., apartment–APART), but it was unclear whether this priming effect was distinct from that obtained with purely orthographic primes.

A similar study by Dominguez, Segui, and Cuetos (2002) compared semantic, orthographic, and morphological priming to unrelated and identity priming in a lexical decision task in Spanish. They used masked primes with 32- and 64-ms SOAs as well as unmasked primes with a 250-ms SOA and found equivalent facilitation for orthographically and morphologically related pairs at 32 ms. At 64 ms, both the morphological primes and the orthographic primes again produced facilitation, but the effect was greater for the morphological primes. At these SOAs there was no semantic priming effect. However, at 250 ms, they obtained facilitation for the morphological and semantic primes, but inhibition for the orthographic primes. These data, along with the results of Rastle et al. (2000), provide strong evidence that amorphologically structured level of representation plays an important role in visual word recognition, and suggest that early morphological influences can be obtained independently of semantic relatedness, which should only influence morphological priming at longer prime durations (Feldman, Barac-Cikoja, & Kostic, 2002; Feldman, Soltano, Pastizzo, & Francis, 2004; Marslen-Wilson et al., 1994).

These morphological priming effects can be accommodated by two classes of hypotheses distinguished by the putative locus of such effects. According to the supralexical hypothesis (e.g., Giraudo & Grainger, 2001), morphological relations between words are represented in the way whole-word form representations are connected at a higher level, and this connectivity is determined by semantic transparency. Therefore, on this account, morphological priming should always be greater with transparent primes. According to the sublexical hypothesis, (e.g., Taft & Forster, 1975) on the other hand, a given linguistic input is subject to morphological decomposition before whole-word representations are contacted, such that morphemic representations are extracted from the stimulus independently of semantic transparency. This account therefore predicts equivalent and early priming effects for transparent and opaque primes.

The role of semantic transparency in morphological priming was investigated in a study by Longtin, Segui, and Hallé (2003) using so-called pseudo-derived primes in French. Pseudo-derived primes were defined as monomorphemic words that could be parsed into existing morphemes (e.g., *baguette/bague*; an English example would be *corner*: corn+er). These are to be distinguished from morphologically opaque primes, as tested in the Rastle et al. (2000) study, which are etymologically, but not semantically, related (e.g., *fauvette/fauve*; an English example would be apartment–apart). Longtin et al. reported significant priming from both transparent derived primes (e.g., baker–bake) and pseudo-derived primes (e.g., corner–corn) and no orthographic priming with a prime duration of 46 ms. This fits with the results of Rastle et al., showing significant priming from opaque derived primes with a prime duration of 42 ms.

In a subsequent study, Rastle, Davis, and New (2004) further clarified the nature of the priming effect shown by opaque primes. In previous studies (Marslen-Wilson et al., 1994), opaque prime–target pairs had been defined as those that do not have a semantic relationship yet have a morphological relationship established on etymological grounds (e.g., witness–wit), and orthographic prime–target pairs had been defined as those that have neither a semantic nor historical morphological relationship even if these pairs, on the surface, appeared to be morphologically related (corner–CORN). Rastle et al. argued that a morphological segmentation procedure that operates independently of semantics would be sensitive to the appearance of a morphological relationship rather than etymological concerns. As a result, monomorphemic words such as “corner” may be decomposed regardless of their morphological structure (or lack thereof). Rastle et al. redefined a semantically opaque morphological relationship as one that obtains when primes and targets share an apparent morphological relationship, but no semantic relationship, and a purely orthographic relationship as one that obtains when targets are embedded within monomorphemic primes that are not fully decomposable into a stemand affix (e.g., scandal–SCAN). Following Rastle et al., from now on we use the term “opaque” prime to refer to both etymologically related items (e.g., apartment–APART) and pseudomorphemic items (e.g., corner–CORN).

Rastle et al. (2004) obtained significant priming effects with opaque primes (e.g., brother–BROTH), but obtained no facilitation with orthographic primes, that is, when targets were primed by monomorphemic words that were not fully decomposable into a stem and affix (e.g., scandal–SCAN; see also Giraudo & Grainger, 2001). These data suggest that morphological segmentation procedures operate on any fully decomposable word (or nonword; cf. Longtin & Meunier, 2005) regardless of semantic transparency.

In a further attempt to disentangle the effects of semantic relatedness on morphological priming, Diependaele, Sandra, and Grainger (2005) examined the effects of semantically transparent, semantically opaque, and orthographic primes on target processing using Dutch stimuli and a masked cross-modal priming technique with a prime duration of 53 ms. Because a 13-ms backward mask was used, the total SOA was 67 ms. It was found that only morphologically complex, semantically transparent primes yielded robust facilitation. However, in their discussion, it was suggested that the SOA of 67 ms may have been too long to observe facilitation from opaque primes. This hypothesis is bolstered by the fact that Rastle et al. (2000) observed priming for semantically opaque, morphologically complex primes at SOAs of 43 ms in a masked priming study but not with prime durations of 72 or 230 ms.

To test this hypothesis, in a subsequent experiment Diependaele et al. (2005) used the incremental priming technique developed by Jacobs, Grainger, and Ferrand (1995) to investigate the time course of morphological priming effects in French. This technique involves the gradual increase of prime intensity or duration, starting from a level that is too low to influence target processing. Thus, priming effects can be evaluated not only across but also within conditions. Transparent, opaque, and orthographic primes were compared to unrelated primes at 13-, 40-, and 67-ms prime durations (26-, 53-, and 80-ms SOAs).

The results showed that semantically transparent primes led to facilitation of target processing at 40-ms prime durations but semantically opaque primes did not facilitate target processing until prime durations of 67 ms. In addition to the discrepancy between semantically transparent and opaque primes with respect to the time course of the priming effects, the effect for transparent primes was also larger than that for opaque primes. These data are therefore at odds with those of Rastle et al. (2004) and Longtin et al. (2003), who found equally large priming effects for transparent and opaque primes using a prime duration of approximately 40 ms. Diependaele et al. (2005) suggest that the discrepancies between their results and those of Rastle et al. and Longtin et al. might be attributable to the use of a backward masking procedure in their study. It has been argued that the use of a backward mask leads to interference in letter codes and reduces the degree of activation of the prime (Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003).

Therefore, there are still some inconsistencies in the empirical data concerning the relative strength of priming from transparent and opaque morphological primes and the different time courses of these priming effects. The present study attempts to clarify this situation by using the ERP technique, which is highly sensitive to the time course of processing. This clarification is particularly important given that these priming effects provide a critical test of supralexical and sublexical approaches to morphological representation.

The Electrophysiology of Morphological Processing

In recent years, researchers using behavioral data to test hypotheses about the representation and processing of words have begun to supplement these data with those of other methodologies such as scalp-recorded ERPs. ERPs are well suited to the study of language processing because they have good temporal resolution, which allows for the tracking of perceptual and cognitive processes in real time without requiring participants to produce overt responses that may interfere with the cognitive events related to stimulus processing. Moreover, if it is assumed that distinct processes are mediated by different underlying neurophysiological and neuroanatomical mechanisms, then differences in ERP patterns, for example in polarity, scalp topography, timing, and amplitude, can provide evidence for distinct brain and by extension cognitive mechanisms (Osterhout, 1997).

Particularly relevant for the present study is the recent work showing a number of ERP components that are sensitive to linguistic processes operating in the masked priming paradigm. Like supraliminal priming, masked repetition priming produces a reliable attenuation of the classic N400 component. It is a matter of debate whether the N400 component of the ERP is sensitive to unconscious automatic priming mechanisms or to strategic mechanisms only. Recent studies demonstrating N400 modulation by masked primes at a short SOA have strengthened the notion that the N400 is modulated by automatic spreading activation and not exclusively by strategic semantic processes (Kiefer, 2002). Although a substantial number of studies have shown that the amplitude of this component is primarily sensitive to postlexical processing, in particular the process whereby a word is semantically integrated with the preceding context such that larger N400s are associated with more integration difficulty (Holcomb, 1993), Holcomb, Grainger, and colleagues (Holcomb & Grainger, 2006; Holcomb, Reder, Misra, & Grainger, 2005) have suggested a modification of the semantic integration hypothesis to account for the pattern of N400 effects in the masked priming paradigm. They propose that, in this paradigm, some of the generators of the N400 might also be sensitive to interactivity at the interface between word representations and meaning (form–meaning interface). The initial activity between these levels set in action by the masked prime would then influence subsequent interactions during target processing. This account of the N400 would explain the sensitivity of the N400 component to priming that is partly form based, such as repetition and partial repetition priming (Holcomb & Grainger, 2006).

Using masked priming Holcomb and Grainger also report an effect on an earlier negativity, the N250, which has an onset at ~ 175 ms, a duration of ~ 150 ms, and a peak at ~ 250 ms. Unlike the N400, the N250 is not typically seen in supraliminal priming, as the prime and target have to be very close temporally or the N250 is refractory. In their study the N250 was larger, and peaked earlier, to targets following primes that shared no letters with the target than to targets that shared all but one letter with their primes, which in turn produced larger and earlier N250s than targets that shared all of their letters with the preceding prime. Holcomb and Grainger (2006) suggested that the N250 reflects the processing of letters and letter clusters, and its amplitude may reflect the degree of mismatch between representations activated by the prime and those activated by the target.

In an attempt to disentangle effects of semantic, orthographic, and morphological priming on target processing, in a Spanish language study, Dominguez, de Vega, and Barber (2004) examined ERPs to targets preceded by morphologically related primes, *hij–o/hij–a* (son/daughter), primes that were stem homographs of the target, *foc–o/foc–a* (lightbulb/seal), and unrelated primes, *pavo/meta* (turkey/goal). They found that morphological priming produced an attenuation of the N400 component that they attributed to the ease of semantic integration between primes and targets that not only share part of their meaning but also their stem morpheme. Homographic priming produced an initial attenuation similar to the morphological pairs but then formed a delayed N400. Dominguez et al. attributed this effect to an initial attempt to process the stem homographs as true morphological pairs followed by a failure to achieve semantic integration. Orthographic priming failed to produce any attenuation of the N400 effect.

The Current Study

The goal of the study was to further investigate the role of semantic information in the segmentation of morphologically complex words by examining ERPs to targets primed by semantically transparent, semantically opaque, and orthographically but not morphologically related primes using the masked priming paradigm.

Rastle et al. (2004) redefined a semantically opaque relationship as one that obtains when primes and targets share an apparent morphological relationship but no semantic relationship, and a purely orthographic relationship as one that obtains when targets are embedded within monomorphemic primes that are not fully decomposable into a stem and affix (e.g., scandal–SCAN); that is, when the stem is removed from the word in which it is embedded, the remaining letters do not form a recognizable affix. Following Rastle et al., from now on we use the term "opaque" prime to refer to both etymologically related items (e.g., apartment–APART) and pseudomorphemic items (e.g., corner–CORN).

We compared ERP responses to targets primed by semantically transparent morphologically related primes (e.g., hunter–hunt), semantically opaque morphologically related primes (e.g., corner–corn), and orthographically but not morphologically related primes (e.g., scandal–scan) using the masked priming technique. The supralexical model of lexical representation predicts that morphological priming should occur only with semantically transparent primes and targets because these access common supralexical morphological representations. These morphological representations presumably contact common semantic representations (or are part of a larger semantic network), and it is the activation of these overlapping morpho-semantic representations that results in a reduced N400 component. In contrast, semantically opaque primes and unrelated primes are presumed to activate different supralexical morpho-semantic representations from those activated by their targets, and this difference should result in less facilitation and a larger N400.

The N250, however, is presumed to reflect the processing of subword orthographic representations such as letters and letter clusters that are shared by primes and targets in all the related prime conditions. The supralexical model therefore predicts that semantic transparency should not influence the amplitude of the N250. However, given the importance of morphological structure for prelexical processing in the sublexical model, according to this account we ought to observe stronger priming effects from morphological primes independently of semantic transparency in the N250 ERP component. On the basis of the sublexical model we therefore expect to observe that, in all three conditions, related items will show a reduced N250 component when compared to unrelated items, but that this N250 reduction effect will be greater for items in the transparent and opaque conditions than for items in the orthographic condition.

Methods

Participants

The participants for this study were 25 adults (6 men and 16 women). The electrophysiological and behavioral data from 3 participants were excluded from analysis because of excessive eye movement artifact. The behavioral data from 1 additional subject were not analyzed because of equipment malfunction. All participants were recruited from the Tufts University community and paid for their participation. The participants ranged in age from 18 to 22 years (mean 20.2 years). All were right-handed native English speakers with normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment.

Stimuli

The stimuli were 324 prime–target pairs chosen from the CELEX English database (see the Appendix). One-third (108) of these pairs were morphologically related and had a semantically and orthographically transparent relationship (lender–LEND), one-third were not morphologically related and had a semantically opaque relationship (corner–CORN), and one-third were orthographically but not semantically or morphologically related (scandal–SCAN).

Semantic relatedness norms were obtained for these items by asking 26 members of the Tufts University and Hampshire College communities to rate each pair of related prime and target words with respect to the degree to which they considered them related in meaning with 1 being *very related* and 5 being *completely unrelated*. The mean difference in ratings between items was statistically significant, $F(2,321) = 558.9$, $p<.001$. Pairwise comparisons showed that the ratings in the three priming conditions all differed significantly from each other (all *p*s<.001). The mean rating for the transparent items ($M = 1.57$, $SE = .064$), was less than that for the opaque items ($M = 3.9$, $SE = .064$), which in turn was less than that for orthographic items ($M = 4.4$, $SE = .064$).

The same morphological suffixes appeared in approximately the same proportions in both the transparent and opaque conditions. In the orthographic condition, the characters at the end of the word that did not overlap with the target did not comprise a regularly used English suffix. The stem was the target item for each pair. Across the three conditions, prime–target pairs were matched on log frequency of the target, $F(2,321) = 1.7$, $p<.181$, log frequency of the prime, $F(1,321) = 1.3$, $p<.281$, length of the target, $F(2,321) = 1.9$, $p<.151$, length of the prime, $F(2,321) = 0.5$, $p<0.61$, length of the prime suffix (or in the case of the orthographically related words, the characters at the end of the word that did not overlap with the target), $F(2,321) = .4$, $p<.71$, and neighborhood size of the target, $F(2,321) = 1.5$, $p<.21$. The items were randomly divided into two groups of 162 items, containing 54 prime–target pairs in each condition. Targets that were preceded by a related word in one list were preceded by an unrelated word in the other. Unrelated pairs were formed by randomly re-pairing related pairs, and ensuring that the primes formed by this procedure were neither orthographically nor semantically related to the targets. Each subject saw only each target only once; therefore no subject saw any given target preceded by both a related and an unrelated item.

For the purposes of the lexical decision task, each subject also saw 324 pronounceable nonword targets, preceded by morphologically complex real-word primes. Nonwords were formed by changing one letter of the stem of the prime (e.g., flasher–BLASH). Half of the nonword targets were preceded by the primes from which they had been derived whereas half were preceded by an unrelated prime.

Procedure

Participants were seated in a comfortable chair in a darkened room at a distance of 76 cm from the computer monitor. Each testing session began with a short practice block, followed by the experimental block and then by a prime visibility test. Participants were told that they would see a list of words and nonwords on the computer monitor and were instructed to respond as quickly and as accurately as possible indicating whether the stimulus was a word (dominant hand) or not (nondominant hand) by pressing one of two response keys. All words appeared in white text against a black background. All characters were 60 pixels high × 30 pixels wide on a screen with a resolution of 800 × 600 pixels and a refresh rate of 100 Hz. Primes were presented in lowercase letters for 50 ms, preceded by a 500-ms random consonant forward mask and a 20-ms random consonant backward mask. The mask shared no letters in common with the target or with the prime. The target was then presented in uppercase letters for 300 ms followed by a 1200-ms intertrial interval.

Recording Procedure

EEG activity was recorded from 29 scalp locations using tin electrodes attached to an elastic cap (Electrocap International) according the international 10–20 system (Figure 1).

Vertical eye movements and blinks were monitored by means of an electrode placed beneath the left eye and horizontal eye movements by an electrode placed at the outer canthus of the right eye. These 31 channels were referenced to an electrode placed over the left mastoid, whereas the activity over the right mastoid was actively recorded to monitor for asymmetrical mastoid activity (there was none). EEG signals were amplified with a bandpass of 0.01 to 40 Hz by a SA Bioamplifier system. The data were digitized online at 200 Hz and stored on disk for later analyses. Individual trials containing excessive eye movement artifact (EOG exceeded ± 300 μV) were eliminated before averaging. Artifact-free ERPs were formed by averaging the EEG time-locked to the onset of the prime and included activity up to 800 ms after target onset.

Data Analysis

We calculated the mean voltage in each of two time windows (200–300 ms and 300–500 ms), relative to a 100-ms prestimulus baseline. These time epochs were chosen because they correspond to the latency ranges that have been found for the N250 and the N400 (Holcomb & Grainger, 2006).

Mean amplitude data were analyzed with four separate repeated measures ANOVAs. One ANOVA included the midline sites; the three other analyses included sites located at three bilateral columns running along the rostral–caudal axis (see Figure 1). All four ANOVAs included the factors Prime Type (transparent, opaque, and orthographic), Relatedness (related, unrelated), and Electrode. The three lateral analyses also included the factor Hemisphere (right, left). For the midline ANOVA, the factor Electrode had five levels, (FPZ, FZ, CZ, PZ, OZ), for the inner lateral ANOVA three levels (FC1/2, C3/4, CP1/2), for the midlateral ANOVA four levels (F3/4, FC5/6, CP5/6, P34), and for the outer lateral ANOVA five levels (FP1/2, F7/8, T3/4, T5/6, O1/2).

We also calculated difference scores by subtracting the mean amplitude for the related trials from those for the unrelated trials in order to look for linear trends across the three conditions. Trials characterized by excessive EOG artifact were rejected, resulting in 12.2% of trials being discarded.

We also analyzed reaction times and accuracy rates with a repeated measures analysis of variance with Prime Type and Relatedness as factors. Any responses that were below 200 ms or above 1500 ms were excluded from the analysis.

For both the electrophysiological and the behavioral data, the Geisser–Greenhouse correction was applied when evaluating effects with more than one degree of freedom.

Results

Electrophysiological Data

ERP waveforms at each electrode site and for each experimental condition are shown in Figure 2–Figure 4. The waveforms show the characteristic negative peak at 250 ms after target onset (N250) found in masked repetition priming (e.g., Holcomb & Grainger, 2006) and a later, more temporally distributed negative-going wave peaking at 400 ms after target onset (N400). The data were therefore analyzed using two different time windows centered on these two critical components (200–300 ms and 300–500 ms). Figure 5 shows scalp distributions of priming effect sizes as a function of priming condition at 250 ms and 400 ms after target onset.

200–300 ms—Analyses of data in this time window yielded a significant Relatedness × Prime Type interaction effect at midline, mid-, and outer lateral sites, $F_{mid}(2, 42) = 3.7$, $p<.038$; $F_{mid\_lat}(2, 42) = 4.1$, $p<.028$; $F_{out\_lat}(2.42) = 4.3$, $p<.025$. The effect was not significant at the inner lateral sites, $F_{inn\_lat}(2, 42) = 2.7$, $p<.085$. In all four analyses, there was also a significant Relatedness × Prime Type × Electrode interaction, $F_{mid}(8, 168) = 6.2$, $p<.001$; $F_{inn\_lat}(4, 84) = 6.3$, $p<.003$; $F_{mid\_lat}(6, 126) = 5.5$, $p<.004$; $F_{out\_lat}(8, 168) = 8.3$, $p<.001$. There were no other significant interactions involving both the factors Relatedness and Prime Type.

Follow-up analyses conducted to clarify the Relatedness × Prime Type × Electrode interaction showed that although there were significant differences in the responses to transparent related and transparent unrelated items at frontal sites in all analyses, $p_{FPz}<.001$, $p_{Fz}<.001$, $p_{Cz}<.008$, $p_{FC1/2}<.001$, $p_{C3/4}<.007$, $p_{CP1/2}<.028$, $p_{F3/4}<.001$, $p_{FC5/6}<.001$, $p_{CP5/6}<.011$, $p_{FP1/2}<.001$, $p_{F7/8}<.002$, $p_{T3}<.002$, $p_{T5}<.041$, responses to opaque related and opaque unrelated items only differed at posterior midline sites, $p_{Pz}<.038$; $p_{Oz}<.047$, whereas responses to orthographic related and orthographic unrelated did not differ at any electrode site (see Figure 5).

300–500 ms—Analyses of data in this time window yielded a significant Relatedness × Electrode × Prime Type interaction effect at inner, mid-, and outer lateral sites, $F_{inn\_lat}(2,42) = 3.5$, $p<.045$; $F_{mid\_lat}(2,42) = 4.8$, $p<.016$; $F_{out\_lat}(2,42) = 4.7$, $p<.02$. The effect was marginally significant at the midline sites, $F_{mid}(2,42) = 3.39$, $p<.053$. There were no other significant interactions involving both the factors Relatedness and Prime Type.

Simple effects analyses showed that only for the transparent items did responses to related and unrelated items differ, $p_{mid}<.038$; $p_{inn\_lat}<.71$; $p_{mid\_lat}<.007$; $p_{out\_lat}<.039$, although at midline and outer lateral sites this difference was not significant when corrected for multiple comparisons ($\alpha = .0167$).

Although the priming effect was not significant for items in the opaque and orthographic conditions, inspection of the mean differences across conditions suggested the existence of a linear trend. An analysis of the difference scores allowed us to test this possibility. Orthogonal polynomial contrasts run on the difference scores revealed a significant linear trend, $F_{mid}(1,21) = 6.4$, $p<.02$; $F_{inn\_lat}(1,21) = 7.2$, $p<.011$; $F_{mid\_lat}(1,21) = 7.6$, $p<.011$; $F_{out\_lat}(1,21) = 6.8$, $p<.021$, with items in the transparent condition showing the largest priming effects and items in the orthographic condition the smallest, with items in the opaque condition intermediate between the two.

Reanalyses with ambiguous items removed—The norming of our stimuli with respect to the degree of semantic relatedness between primes and targets revealed that some items in all three categories were ambiguous, in that their rated semantic relatedness did not correspond to the category they had been assigned to. Items in the opaque and orthographic categories that received a score of less that 3 on our rating scale, indicating that participants viewed these items as somewhat semantically related, and items in the transparent category that received a score of greater than 3 on our scale, indicating that participants viewed these items as semantically unrelated, were removed from the data, which were then reanalyzed. Twenty-two items were removed from the set of opaque items, five from the set of orthographic items, and three from the set of transparent items.

The results of this new analysis were broadly similar to those found using the entire data set. In the 200–300-ms time window, we again found a significant Relatedness × Electrode × Prime Type interaction effect at midline, mid-, and outer lateral sites, $F_{mid}(2,42) = 3.3$, $p<.051$; $F_{mid\_lat}(2,42) = 3.47$, $p<.044$; $F_{out\_lat}(2,42) = 4.1$, $p<.028$. The effect was not significant at the inner lateral sites, $F_{inn\_lat}(2,42) = 2.5$, $p<.099$. At midline and outer lateral sites, there was also a significant Relatedness × Prime Type × Electrode interaction, $F_{mid}(8,168) = 2.68$, $p<.049$; $F_{out\_lat}(8,168) = 3.9$, $p<.022$.

Simple effects analyses conducted to clarify the Relatedness × Electrode × Prime Type interaction showed that only for the transparent items did responses to related and unrelated items differ, $p_{mid}<.004$, $p_{mid\_lat}<.003$, $p_{out\_lat}<.003$. Simple effects analyses conducted to clarify the Relatedness × Prime Type × Electrode interaction showed that the greatest differences were between transparent related and transparent unrelated items at frontal sites, $p_{FPz}<.001$, $p_{Fz}<.001$, $p_{Cz} = .008$, $p_{FP1/2}<.001$, $p_{F7/8}.004$, $p_{T3}<.002$. Responses to related and unrelated items did not differ in either the orthographic or the opaque conditions.

However, an inspection of the mean differences across conditions suggested the existence of a linear trend, and orthogonal polynomial contrasts confirmed this hypothesis, $F_{mid}(1,21) = 5.57$ $p<.028$; $F_{inn\_lat}(1,21) = 4.5$, $p<.047$; $F_{mid\_lat}(1,21) = 5.06$, $p<.036$; $F_{out\_lat}(1,21) = 5.28$, $p<.033$. Items in the transparent condition showed the largest priming effects and items in the orthographic condition the smallest, with items in the opaque condition intermediate between the two.

In the 300–500-ms time window, we found a significant Relatedness × Prime Type interaction effect at mid-, and outer lateral sites, $F_{mid\_lat}(2,42) = 4.44$, $p<.02$; $F_{out\_lat}(2,42) = 4.8$, $p<.02$. The effect was marginally significant at midline and inner lateral sites, $F_{mid}(2,42) = 3.1$, $p<.068$; $F_{inn\_lat}(2,42) = 3.2$, $p<.058$. Simple effects analyses conducted to clarify this interaction showed that at mid- and outer lateral sites, only for the transparent items did responses to related and unrelated items differ, $p_{mid\_lat}<.007$, $p_{out\_lat}<.033$, although at outer lateral sites this difference was not significant when corrected for multiple comparisons. We also analyzed the difference scores so as to directly compare the size of the effect across all three conditions. Orthogonal polynomial contrasts run on these scores revealed a significant linear trend, $F_{mid}(1,21) = 7.3$, $p<.013$; $F_{inn\_lat}(1,21) = 7.9$, $p<.011$; $F_{mid\_lat}(1,21) = 9.03$, $p<.008$; $F_{out\_lat}(1,21) = 9.2$, $p<.007$, with items in the transparent condition showing the largest priming effects.

Behavioral Data

Analyses of the reaction time data revealed a significant Prime Type × Relatedness interaction, $F(2,40) = 17.3$, $p<.001$. Comparisons of responses to related and unrelated items for each Prime Type showed that only for the transparent items did responses to related and unrelated items differ, $p_{mid}<.038$, $p_{inn\_lat}<.71$, $p_{mid\_lat}<.007$, $p_{out\_lat}<.039$.

As with our electrophysiological data, although the priming effect was not significant for items in the opaque and orthographic conditions, inspection of the mean differences across conditions suggested the existence of a linear trend. An analysis of the difference scores allowed us to test this possibility. Orthogonal polynomial contrasts run on the difference scores revealed a significant linear trend, $F(1,20) = 31.2$, $p<.001$, with items in the transparent conditions showing the greatest priming effects and those in the orthographic condition the least. Table 1 provides mean reaction times and accuracy rates for each condition. Pairwise comparisons revealed that both transparent ($p<.001$) and opaque ($p<.005$) items showed significantly greater priming effects than orthographic items. Transparent and OPAQUE items did not differ ($p>.1$).

For the accuracy data, there were no significant main effects ($p>.4$).

Discussion

The purpose of this study was to investigate the role of semantic information in the segmentation of morphologically complex words and, in particular, to compare predictions of the sublexical and supralexical models of morphological representation by examining ERPs to targets primed by semantically transparent, semantically opaque, and orthographically but not morphologically related primes.

In the N250 time window, we found that responses to unrelated items in the transparent condition were significantly more negative than those to related items. Although unrelated items in the opaque condition did generate greater negativities than the related items, these were only apparent at midline sites and were more posterior in their distribution than those found for items in the transparent condition. However, when we reanalyzed the data after removing items from the opaque condition which according to the norming data were semantically related, then these effects were no longer apparent. This therefore suggests that the overall pattern was generated by the opaque items that were judged to be semantically related. Responses to related and unrelated orthographic items did not differ. Nevertheless, the presence of a significant linear trend in the priming effect sizes for these three conditions suggests that semantic transparency might be having a graded influence on priming effects, with transparent primes generating the largest effects, orthographic primes the smallest, and opaque primes in between.

In the N400 time window, we found that responses to unrelated items were significantly more negative than those to related items only in the transparent condition. Responses to related and unrelated opaque and orthographic items did not differ. However, as with the N250 analyses, comparison of the mean differences between unrelated and related items across conditions revealed the existence of a significant linear trend, with transparent items showing the greatest effects and orthographic items the smallest.

In the reaction time data, only for the transparent items did responses to related and unrelated items differ; however, these data also showed a similar linear trend. Thus both the N400 data and the behavioral results show clear differences only between unrelated and related items that are semantically transparent but also suggest that there are graded effects of priming as a function of semantic transparency and morphological structure.

These results are not predicted by either the prelexical decomposition model of Taft and Forster (1975), nor by the supralexical model of Giraudo and Grainger (2001). The former would predict equivalent priming effects for the opaque and transparent conditions and weaker effects for the orthographic condition; the latter would predict priming for the transparent condition but an equivalent lack of priming for the orthographic and opaque conditions.

The very fact that morphological priming effects were found in the early N250 ERP component would, at first sight, appear more in line with a prelexical approach. This would therefore appear to fit with Rastle et al.'s (2004) proposal for the existence of morphemically structured prelexical orthographic representations that are not governed by semantic transparency (i.e., the sublexical hypothesis). However, our data do not support such an analysis. If this were the case, we should find equivalent priming for the transparent and opaque conditions. Both conditions contain complex primes that are fully decomposable into morphologically legal stems and affixes. However, we found that the opaque priming effect was no longer significant when semantically related items were removed from this category of stimuli.

The graded effects of priming found in our data, as revealed by significant linear trends in the effect sizes across priming conditions, could well reflect the fact that there was a graded change in semantic transparency across our three priming conditions. A norming study performed on our stimuli showed that transparent primes were judged to be most strongly related to targets and orthographic primes most unrelated to targets, with opaque items showing an intermediate level of semantic relatedness. Given that our three types of related primes were matched for orthographic overlap with targets, the norming data suggest that it is the differences in prime–target semantic relatedness that is driving the differences in priming effects on ERPs and in the behavioral data. Also, the fact that the N400 priming effects showed similar topographical distributions for transparent, opaque, and orthographic priming suggests that the same neural generators are at play in all three conditions, but to different degrees. This finding is in line with the fMRI results of Devlin, Jamison, Matthews, and Gonnerman (2004), showing largely overlapping brain regions associated with priming from morphological, semantic, and orthographic primes in a masked priming study.

The influence of semantic transparency on priming effects in the N250 is in favor of amore interactive account of such priming effects. According to this account, the N250 ERP component would reflect a state of resonance between prelexical (bottom-up) and lexical–semantic (top-down) representations, and not just bottom-up prelexical activation or only top-down semantic activation (see Holcomb, Grainger, & O'Rourke, 2002, for a resonance account of the N400). This account of N250 priming effects is in line with the fact that a pure semantic priming manipulation has not been found to affect the N250 in masked priming (Grossi, 2006). When a semantically transparent prime (e.g., "hunter") activates its embedded stem ("hunt"), the subsequent processing of the target "hunt" benefits from the compatibility between activated prelexical form representations and higher level semantic representations. This does not occur with opaque and orthographic primes, given the semantic incompatibility between the prime word's meaning and the meaning of the target word. This interactive account of relatively early morphological priming effects (i.e., in the N250 component) does not need to posit the existence of explicit morphological representations (e.g., Plaut & Gonnerman, 2000). Nevertheless, the interactive account is perfectly compatible with the supralexical model of morphological representation, according to which the semantic relations between morphologically related words have a special status within a more general semantic network (Voga & Grainger, in press). What is critical in this account of morphological priming is that it is the cooperation of form and meaning that is the mechanism driving such effects independently of the precise nature of form and meaning representations (i.e., whether or not one ascribes a special status to morphological relations).

It is also possible that the semantic effect on N250 amplitude is the result of semantic influences on the development of lexical and prelexical form representations that occur during language learning. Interconnectivity across whole-word form representations could be modified as a function of relatedness in form and meaning, such that words like "hunt" and "hunter" might develop mutually excitatory connections as opposed to the mutually inhibitory connections that would develop in the case of "corn" and "corner." In this case, the effects of semantic transparency on N250 amplitude would reflect a modulation of the interactivity between lexical and prelexical form representations during target word processing. Alternatively, it could be the salience of prelexical representations that is affected by semantic transparency during learning, such that a root morpheme like "bake" would develop in strength as an appropriate unit for prelexical decomposition given its occurrence in semantically related words such as "baker" and "bakery."

Summing up, the results of the present experiment show masked priming effects that vary as a function of morphological structure and semantic transparency. These results are difficult to reconcile with either a prelexical decomposition account (Taft & Forster, 1975) or a supralexical account (Giraudo & Grainger, 2001) of morphological representation. One account of these data proposes that morphological priming is driven by an interactive process involving both prelexical form representations and higher level lexical or semantic representations. The N250 ERP component was found to be affected by semantic transparency, suggesting an early influence of top-down feedback on on-going prelexical processing. Semantic transparency continued to influence later processing reflected by the N400 ERP component and overt behavioral responses.

Acknowledgments

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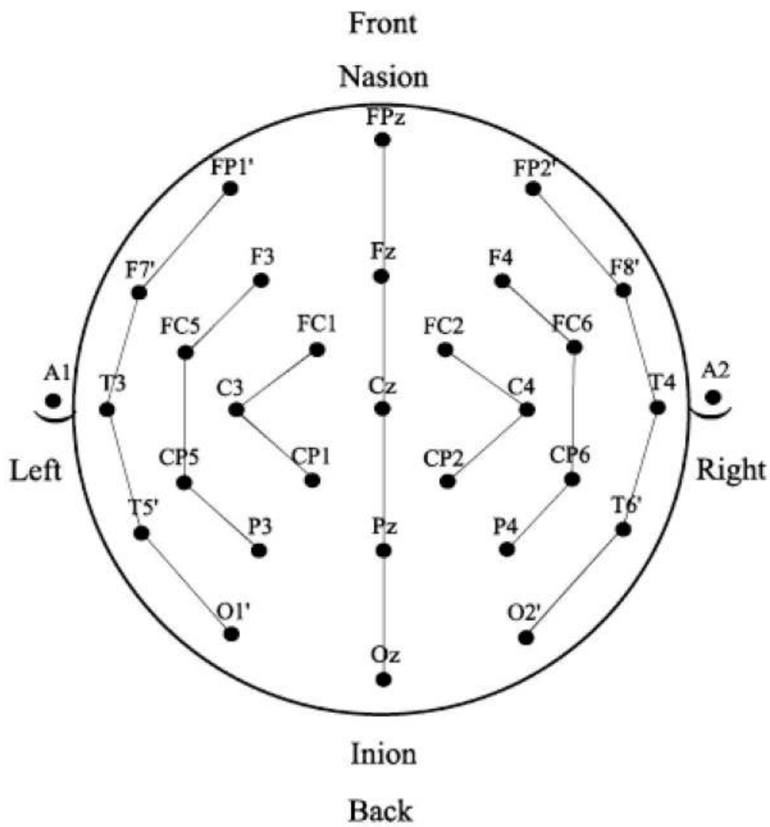

Figure 1.
The 32-electrode montage. The lines connecting the electrode sites show the locations of the midline and bilateral parasagittal columns used in the statistical analysis of the data.

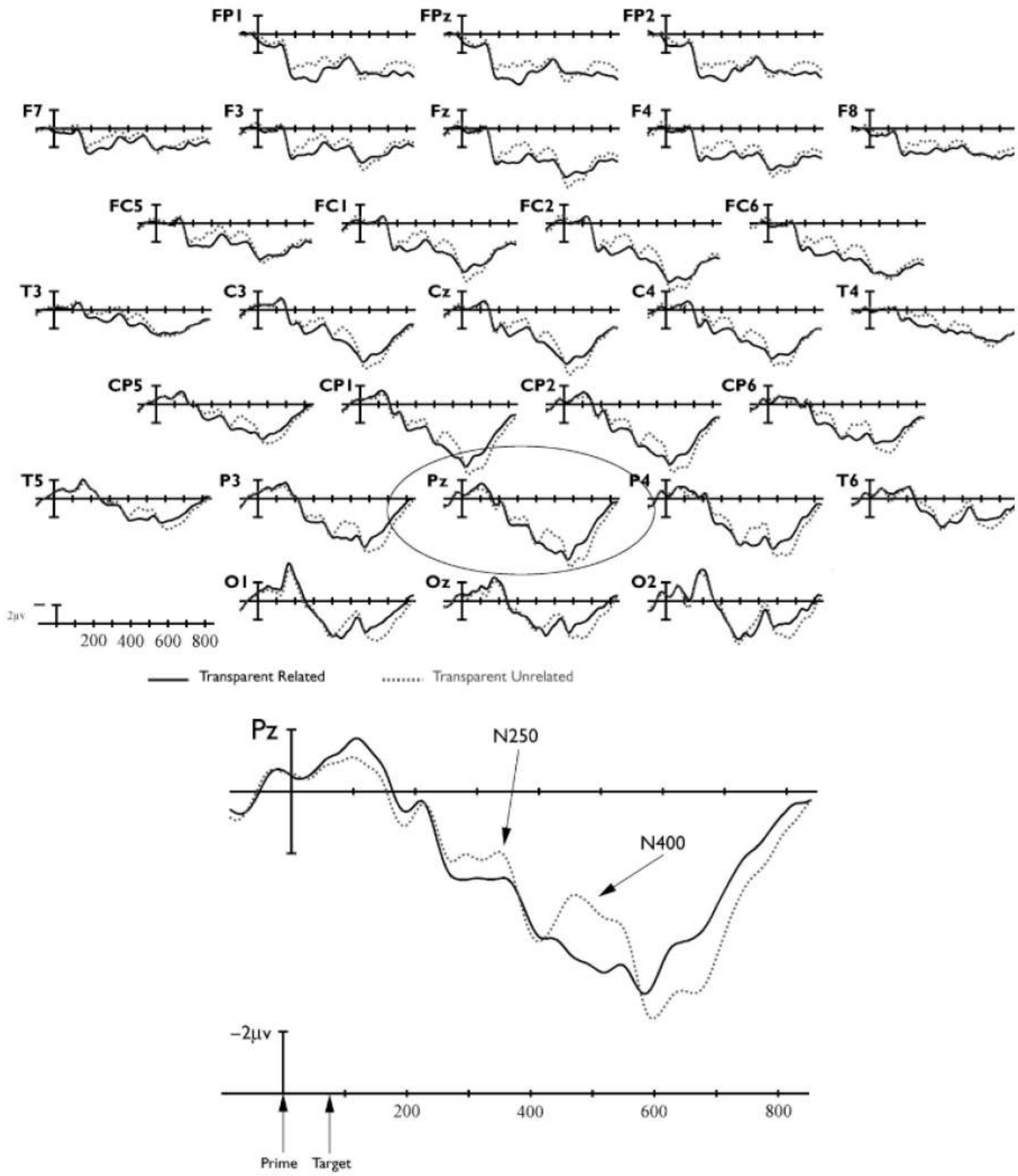

Figure 2.

Grand average ERP waveforms for related (solid lines) and unrelated (dotted lines) targets in the transparent condition at 29 scalp electrode sites. At the bottom of the figure the parietal site Pz is depicted on a larger scale illustrating the N250 and N400 effects.

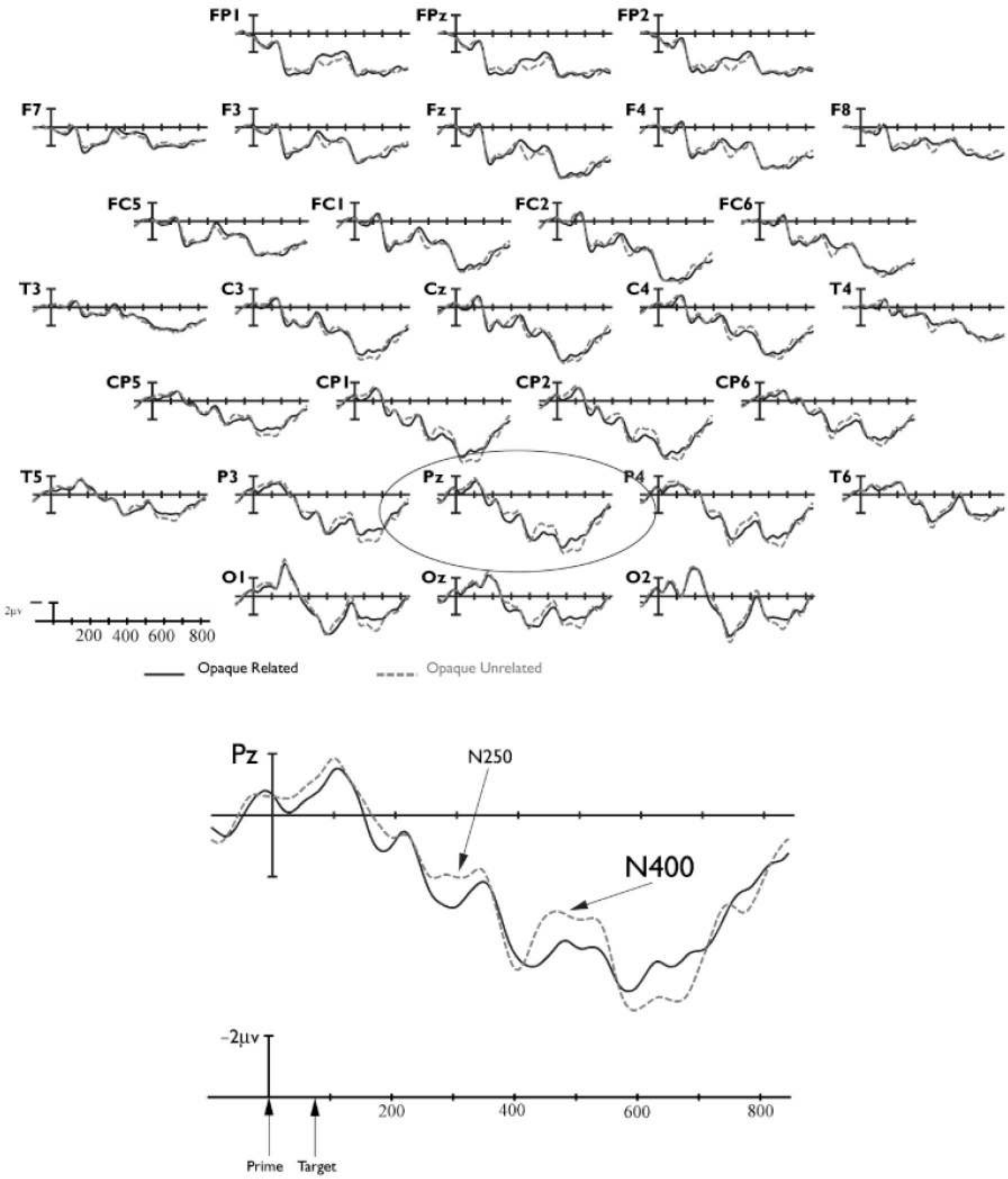

Figure 3.

Grand average ERP waveforms for related (solid lines) and unrelated (dotted lines) targets in the opaque condition at 29 scalp electrode sites. At the bottom of the figure the parietal site Pz is depicted on a larger scale illustrating the N250 and N400 effects.

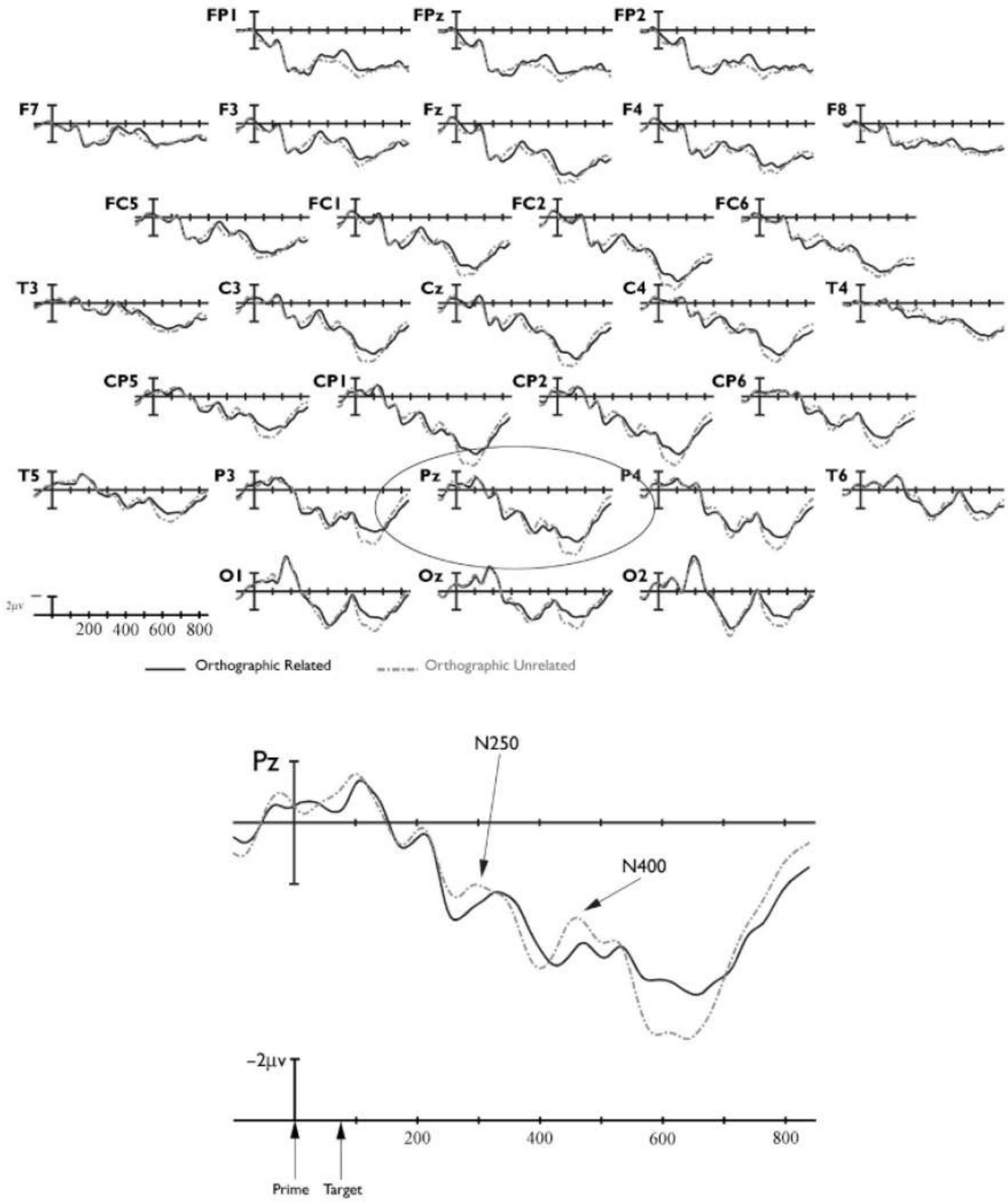

Figure 4.

Grand average ERP waveforms for related (solid lines) and unrelated (dotted lines) targets in the orthographic condition at 29 scalp electrode sites. At the bottom of the figure the parietal site Pz is depicted on a larger scale illustrating the N250 and N400 effects.

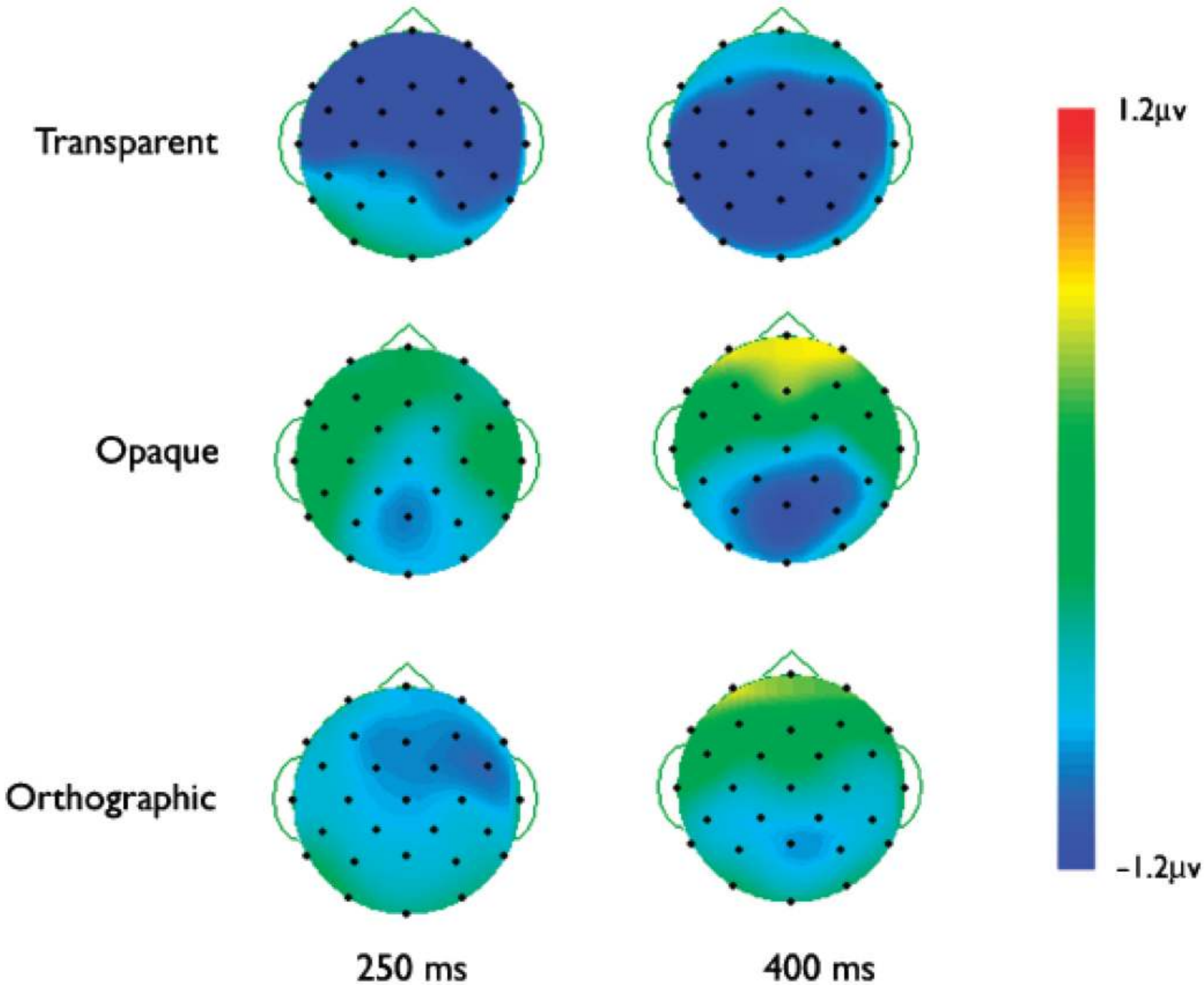

Figure 5.
The spatial distribution of the N250 and N400 at the scalp surface for the transparent (top), opaque (middle), and orthographic (bottom) conditions. These maps were formed from difference waves calculated by subtracting the related from the unrelated conditions.

Table 1

Mean Reaction Times (RT in Milliseconds) and Accuracy Rates toWord Targets in Each Experimental Condition with Standard Errors of the Mean (SE) in Parentheses

	Transparent		Opaque		Orthographic	
Relatedness	**Mean RT (SE)**	**Mean accuracy (SE)**	**Mean RT (SE)**	**Mean accuracy (SE)**	**Mean RT (SE)**	**Mean accuracy (SE)**
Related	626 (20.1)	92.4 (1.7)	655 (22.0)	86.6 (1.9)	675 (20.1)	84.9 (1.7)
Unrelated	669 (19.5)	92.8 (1.7)	682 (19.7)	85.1 (1.9)	676 (19.0)	84.9 (2.2)
Priming effect	43		27		1	

APPENDIX Table A1

Stimuli and Characteristics of Stimuli Used in the Experiment

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Orthographic	strumpet	strum	4	0.30	0.00	0.60	0.00	4.68
Orthographic	burrow	burr	9	1.04	0.30	1.30	0.30	3.76
Orthographic	produce	prod	10	1.11	0.30	2.76	1.52	4.42
Orthographic	nickel	nick	12	1.46	0.30	1.58	0.48	4.54
Orthographic	analog	anal	0	1.53	0.48	1.52	0.48	4.65
Orthographic	spinach	spin	7	1.81	0.60	1.88	0.70	4.27
Orthographic	manicure	manic	5	1.91	0.78	0.95	0.00	4.58
Orthographic	wrench	wren	1	2.00	0.78	1.72	0.60	4.69
Orthographic	singular	sing	16	2.01	0.85	1.92	0.70	5.00
Orthographic	strident	stride	5	2.13	0.95	1.67	0.60	4.76
Orthographic	example	exam	1	2.16	0.95	3.64	2.38	2.81
Orthographic	match	mat	32	2.29	1.08	2.92	1.67	4.65
Orthographic	sternum	stern	1	2.33	1.11	0.90	0.00	4.92
Orthographic	mistake	mist	14	2.36	1.15	2.93	1.68	4.85
Orthographic	pillow	pill	16	2.37	1.15	2.39	1.18	4.54
Orthographic	gazelle	gaze	12	2.46	1.23	1.15	0.30	4.92
Orthographic	slumber	slum	10	1.96	0.78	1.61	0.48	4.73
Orthographic	chaplain	chap	8	2.58	1.34	1.93	0.78	4.73
Orthographic	bellow	bell	15	2.71	1.46	1.11	0.30	4.85
Orthographic	bushel	bush	13	2.88	1.63	1.26	0.30	3.88
Orthographic	earth	ear	12	2.88	1.63	3.34	2.09	4.23
Orthographic	hearth	hear	19	2.92	1.68	1.91	0.70	3.62
Orthographic	decadent	decade	2	2.96	1.72	1.51	0.48	4.85
Orthographic	plantain	plant	5	3.10	1.86	0.95	0.00	4.85
Orthographic	callus	call	16	3.20	1.95	0.30	0.00	4.00
Orthographic	window	wind	15	3.28	2.03	3.38	2.12	4.08
Orthographic	caress	care	26	3.31	2.06	1.34	0.30	4.73
Orthographic	wanton	want	14	3.47	2.21	1.38	0.30	4.73
Orthographic	lateral	late	24	3.56	2.31	2.32	1.11	4.85

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Orthographic	carbon	carb	23	3.69	2.44	2.03	0.85	2.35
Orthographic	lesson	less	19	3.92	2.66	2.68	1.45	3.64
Orthographic	ethereal	ether	2	0.00	0.00	0.00	0.00	4.85
Orthographic	appendix	append	0	0.30	0.00	2.08	0.90	4.88
Orthographic	international	intern	1	0.78	0.00	3.34	2.09	4.88
Orthographic	inferno	infer	2	1.04	0.30	1.58	0.48	2.77
Orthographic	twitch	twit	3	1.18	0.30	1.72	0.48	3.96
Orthographic	galaxy	gala	5	1.20	0.30	2.06	0.85	4.27
Orthographic	stubborn	stub	4	1.45	0.48	2.13	0.90	4.92
Orthographic	brothel	broth	5	1.52	0.48	1.69	0.60	4.65
Orthographic	studio	stud	5	1.56	0.48	2.60	1.36	3.50
Orthographic	heaven	heave	6	1.57	0.48	2.77	1.53	4.85
Orthographic	arsenal	arse	3	1.69	0.60	2.00	0.85	4.81
Orthographic	dialog	dial	5	1.72	0.48	2.45	1.23	4.85
Orthographic	basilica	basil	5	1.89	0.70	1.08	0.30	4.77
Orthographic	fuselage	fuse	6	1.95	0.78	1.30	0.30	4.62
Orthographic	salmonella	salmon	2	2.04	0.85	1.15	0.30	4.85
Orthographic	surface	surf	4	2.06	0.85	3.24	1.99	4.73
Orthographic	surgeon	surge	3	2.11	0.90	2.17	0.95	3.65
Orthographic	villain	villa	2	2.22	1.00	1.86	0.70	4.85
Orthographic	twinkle	twin	3	2.45	1.23	1.26	0.30	4.85
Orthographic	plush	plus	3	2.92	1.68	1.67	0.60	4.92
Orthographic	phonetic	phone	3	3.06	1.82	1.04	0.30	3.92
Orthographic	parenthesis	parent	1	3.10	1.86	1.11	0.30	2.88
Orthographic	freeze	free	4	3.56	2.31	1.98	0.78	4.77
Orthographic	corporate	corpora	0	0.60	0.00	2.39	1.18	4.73
Orthographic	sparse	spar	10	1.00	0.00	1.78	0.60	3.92
Orthographic	trollop	troll	2	1.18	0.30	0.30	0.00	4.88
Orthographic	scandal	scan	8	1.32	0.48	2.34	1.11	4.76
Orthographic	grammar	gram	11	1.72	0.60	2.45	1.23	4.35

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Orthographic	taciturn	tacit	1	1.73	0.60	1.49	0.48	3.96
Orthographic	marinade	marina	2	1.93	0.78	1.28	0.30	4.65
Orthographic	skill	ski	2	1.97	0.78	2.84	1.59	3.77
Orthographic	general	gene	2	2.06	0.85	3.74	2.49	4.92
Orthographic	coupon	coup	6	2.09	0.90	1.04	0.30	3.00
Orthographic	carton	cart	19	2.17	0.95	1.69	0.60	2.54
Orthographic	dragon	drag	8	2.23	1.00	2.13	0.95	4.08
Orthographic	modern	mode	15	2.33	1.11	3.48	2.23	3.73
Orthographic	pumpkin	pump	11	2.36	1.15	1.49	0.48	4.62
Orthographic	grimace	grim	10	2.43	1.20	1.84	0.70	4.85
Orthographic	rational	ratio	3	2.46	1.23	2.70	1.46	4.58
Orthographic	dollop	doll	12	2.50	1.26	1.20	0.30	4.88
Orthographic	regiment	regime	0	2.54	1.30	2.26	1.04	4.81
Orthographic	catch	cat	25	2.87	1.62	2.61	1.38	4.62
Orthographic	coalesce	coal	8	2.88	1.63	0.70	0.00	4.88
Orthographic	cardinal	card	14	2.89	1.64	2.29	1.08	4.50
Orthographic	shallow	shall	7	2.91	1.67	2.45	1.23	4.58
Orthographic	starch	star	10	2.98	1.73	1.96	0.78	4.81
Orthographic	tallow	tall	17	3.06	1.81	1.34	0.30	4.77
Orthographic	tease	tea	15	3.20	1.95	1.53	0.48	3.68
Orthographic	ballot	ball	20	3.22	1.97	2.15	0.95	4.77
Orthographic	wallop	wall	16	3.38	2.12	0.95	0.00	4.73
Orthographic	wallow	wall	5	3.38	2.12	1.08	0.00	4.12
Orthographic	restrict	rest	13	3.57	2.32	1.45	0.48	4.23
Orthographic	pastoral	past	18	3.69	2.44	1.93	0.78	4.72
Orthographic	partner	part	19	3.94	2.68	2.66	1.43	4.88
Orthographic	demonstrate	demon	5	0.00	0.00	1.88	0.70	4.77
Orthographic	stunt	stun	5	0.48	0.00	1.81	0.60	4.81
Orthographic	shunt	shun	6	0.70	0.00	0.30	0.00	4.48
Orthographic	squawk	squaw	3	1.11	0.30	0.78	0.00	3.44

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Orthographic	colonel	colon	1	1.15	0.30	3.21	1.96	4.85
Orthographic	command	comma	1	1.34	0.30	2.92	1.67	4.54
Orthographic	weird	weir	2	1.43	0.30	2.11	0.90	4.73
Orthographic	electron	elect	2	1.52	0.48	2.04	0.85	4.32
Orthographic	shovel	shove	4	1.56	0.48	1.79	0.60	4.65
Orthographic	candidacy	candid	0	1.62	0.48	1.34	0.30	4.08
Orthographic	smuggle	smug	4	1.65	0.48	0.85	0.00	4.84
Orthographic	quartz	quart	2	1.76	0.60	1.23	0.30	4.85
Orthographic	pulpit	pulp	4	1.85	0.70	1.88	0.70	3.19
Orthographic	rabbit	rabbi	0	1.98	0.78	2.28	1.08	4.84
Orthographic	stirrup	stir	1	2.02	0.85	1.30	0.30	4.73
Orthographic	button	butt	5	2.06	0.85	2.45	1.20	4.58
Orthographic	scrape	scrap	4	2.09	0.90	1.56	0.48	4.69
Orthographic	stampede	stamp	4	2.30	1.08	1.41	0.30	4.77
Orthographic	sight	sigh	4	2.32	1.11	3.23	1.98	3.04
Orthographic	plaintiff	plain	4	2.98	1.73	1.49	0.48	4.58
Orthographic	glade	glad	3	3.06	1.81	1.38	0.30	4.38
Orthographic	extract	extra	0	3.16	1.91	2.12	0.90	4.04
Orthographic	forceps	force	3	3.41	2.16	1.00	0.30	4.88
Opaque	skewer	skew	5	0.00	0.00	1.20	0.30	2.96
Opaque	temper	temp	2	0.78	0.00	2.44	1.20	2.38
Opaque	covenant	coven	7	0.85	0.00	2.07	0.90	2.96
Opaque	wager	wag	21	1.08	0.00	1.15	0.30	4.35
Opaque	clamor	clam	7	1.18	0.30	1.81	0.60	2.69
Opaque	tower	tow	22	1.65	0.48	2.91	1.66	3.38
Opaque	master	mast	21	1.67	0.60	2.92	1.68	4.35
Opaque	quarter	quart	2	1.76	0.60	2.97	1.72	4.92
Opaque	sector	sect	5	1.76	0.60	2.99	1.75	4.69
Opaque	finance	fin	21	1.82	0.70	2.66	1.43	4.27
Opaque	dormant	dorm	8	1.86	0.70	1.78	0.60	3.81

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Opaque	rampage	ramp	10	1.90	0.70	1.08	0.30	4.23
Opaque	beaker	beak	12	1.94	0.78	1.34	0.30	4.73
Opaque	limber	limb	6	2.14	0.95	1.04	0.00	4.88
Opaque	tuber	tub	13	2.15	0.95	0.70	0.00	4.19
Opaque	witness	wit	15	2.28	1.08	2.49	1.26	2.31
Opaque	banal	ban	27	2.30	1.08	1.74	0.60	2.88
Opaque	charter	chart	5	2.38	1.15	2.16	0.95	3.35
Opaque	glower	glow	5	2.40	1.18	0.48	0.00	4.08
Opaque	tender	tend	12	2.47	1.23	2.55	1.30	4.73
Opaque	pigment	pig	16	2.51	1.28	1.51	0.48	3.85
Opaque	stringent	string	5	2.60	1.36	1.77	0.60	4.54
Opaque	corner	corn	17	2.64	1.40	3.26	2.01	4.88
Opaque	bowler	bowl	10	2.68	1.45	2.05	0.90	4.42
Opaque	rodent	rod	20	2.70	1.46	1.18	0.30	4.40
Opaque	sandal	sand	15	2.98	1.73	1.30	0.30	3.00
Opaque	fallible	fall	13	3.05	1.80	1.49	0.48	4.23
Opaque	massage	mass	22	3.28	2.03	1.81	0.60	3.35
Opaque	former	form	11	3.63	2.37	3.16	1.91	4.58
Opaque	factor	fact	5	3.96	2.71	2.90	1.65	4.38
Opaque	center	cent	15	4.00	2.75	3.50	2.24	3.54
Opaque	scullery	scull	1	0.00	0.00	1.70	0.60	4.42
Opaque	stilted	stilt	4	0.00	0.00	1.28	0.30	4.72
Opaque	splinter	splint	1	1.11	0.30	1.43	0.30	3.62
Opaque	trolley	troll	2	1.18	0.30	1.98	0.78	4.88
Opaque	grueling	gruel	1	1.36	0.30	1.40	0.30	3.42
Opaque	cryptic	crypt	1	1.41	0.30	1.65	0.48	3.92
Opaque	inventory	invent	4	1.58	0.48	1.83	0.70	4.69
Opaque	glossary	gloss	4	1.63	0.48	1.00	0.30	3.96
Opaque	putty	putt	5	1.70	0.60	1.32	0.30	3.16
Opaque	plumage	plum	6	1.72	0.60	1.30	0.30	4.81

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Opaque	number	numb	1	1.85	0.70	3.76	2.51	4.77
Opaque	crooked	crook	4	1.95	0.78	1.95	0.78	4.08
Opaque	discern	disc	3	2.15	0.95	1.15	0.30	4.69
Opaque	brisket	brisk	3	2.17	0.95	1.11	0.30	4.92
Opaque	archer	arch	3	2.36	1.15	1.98	0.78	4.73
Opaque	organic	organ	0	2.38	1.15	2.44	1.20	4.65
Opaque	early	earl	6	2.44	1.20	3.76	2.50	2.19
Opaque	infantry	infant	1	2.57	1.34	2.16	0.95	4.77
Opaque	coaster	coast	3	2.94	1.69	1.20	0.30	4.46
Opaque	counter	count	3	3.01	1.76	2.71	1.46	4.85
Opaque	boarder	board	3	3.19	1.94	0.78	0.00	3.62
Opaque	signet	sign	1	3.21	1.96	1.11	0.30	3.58
Opaque	hearty	heart	4	3.41	2.16	1.93	0.78	4.77
Opaque	render	rend	17	0.30	0.00	1.36	0.30	2.69
Opaque	scamper	scamp	4	0.78	0.00	0.85	0.00	4.77
Opaque	welter	welt	14	0.95	0.00	1.41	0.30	4.27
Opaque	several	sever	7	1.00	0.30	3.63	2.38	4.65
Opaque	gallant	gall	17	1.43	0.30	1.86	0.70	4.84
Opaque	wicker	wick	12	1.61	0.48	1.83	0.70	3.23
Opaque	mother	moth	6	1.72	0.60	3.87	2.61	4.81
Opaque	traitor	trait	3	1.75	0.60	2.04	0.85	4.81
Opaque	tractable	tract	4	1.77	0.60	1.11	0.30	4.42
Opaque	supplement	supple	1	1.78	0.60	2.13	0.90	4.04
Opaque	proper	prop	12	1.86	0.70	3.07	1.82	3.38
Opaque	literal	liter	8	1.89	0.70	1.92	0.78	4.72
Opaque	bunker	bunk	15	1.99	0.78	2.11	0.90	4.50
Opaque	hinder	hind	11	2.08	0.85	1.08	0.30	3.42
Opaque	inner	inn	8	2.23	1.00	2.91	1.67	4.54
Opaque	luster	lust	12	2.24	1.04	1.51	0.48	3.96
Opaque	mister	mist	14	2.36	1.15	1.84	0.70	2.73

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Opaque	pillage	pill	16	2.37	1.15	0.95	0.00	3.04
Opaque	ponder	pond	8	2.41	1.18	1.08	0.30	2.69
Opaque	customer	custom	0	2.45	1.23	2.41	1.18	4.27
Opaque	penance	pen	24	2.54	1.30	1.41	0.30	3.23
Opaque	hostage	host	11	2.57	1.34	1.60	0.48	4.46
Opaque	message	mess	15	2.66	1.41	3.08	1.84	4.23
Opaque	flourish	flour	2	2.67	1.43	1.92	0.78	4.50
Opaque	tailor	tail	14	2.74	1.49	1.65	0.48	4.19
Opaque	flower	flow	11	2.81	1.57	2.68	1.45	4.58
Opaque	shower	show	13	3.27	2.03	2.47	1.23	4.38
Opaque	hospitality	hospital	0	3.28	2.03	2.07	0.90	4.42
Opaque	canal	can	24	3.87	2.62	2.33	1.11	2.64
Opaque	lateral	later	12	3.87	2.62	2.32	1.11	3.23
Opaque	bother	both	6	4.04	2.79	2.28	1.04	2.04
Opaque	manage	man	34	4.25	3.00	2.23	1.00	2.77
Opaque	ample	amp	8	0.90	0.00	2.28	1.08	1.85
Opaque	sniper	snip	4	0.90	0.00	1.34	0.30	4.88
Opaque	whisker	whisk	1	1.23	0.30	0.85	0.00	4.62
Opaque	plucky	pluck	2	1.32	0.30	1.15	0.30	4.85
Opaque	department	depart	1	1.46	0.48	3.30	2.05	4.73
Opaque	gluten	glut	4	1.48	0.48	1.20	0.30	3.69
Opaque	amenable	Amen	1	1.64	0.48	1.70	0.60	3.62
Opaque	facetious	facet	4	1.67	0.60	1.18	0.30	4.15
Opaque	buzzard	buzz	1	1.76	0.60	1.32	0.30	2.88
Opaque	flicker	flick	5	1.77	0.60	1.88	0.70	4.69
Opaque	question	quest	1	2.06	0.85	3.71	2.46	4.20
Opaque	crafty	craft	4	2.12	0.90	1.56	0.48	2.88
Opaque	ration	rat	28	2.20	1.00	1.98	0.78	2.46
Opaque	brandy	brand	4	2.28	1.04	2.47	1.23	3.23
Opaque	treaty	treat	2	2.38	1.15	2.45	1.23	2.58

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Opaque	fleeting	fleet	2	2.41	1.18	1.96	0.78	2.88
Opaque	liquidate	liquid	0	2.71	1.46	0.70	0.00	4.92
Opaque	fruitless	fruit	0	2.71	1.48	1.66	0.60	2.50
Opaque	united	unit	1	3.06	1.81	3.53	2.27	3.08
Opaque	irony	iron	3	3.09	1.84	2.36	1.15	4.27
Opaque	secretary	secret	0	3.21	1.96	3.19	1.94	2.81
Opaque	courteous	court	1	3.35	2.10	1.98	0.78	2.69
Transparent	vendor	vend	11	0.00	0.00	0.00	0.00	1.31
Transparent	editor	edit	2	0.85	0.00	2.70	1.46	1.54
Transparent	buoyant	buoy	3	1.00	0.00	1.80	0.60	2.85
Transparent	cynical	cynic	1	1.38	0.30	2.19	1.00	1.15
Transparent	flexible	flex	9	1.53	0.30	2.39	1.18	1.62
Transparent	different	differ	1	1.68	0.60	3.86	2.60	1.54
Transparent	sailor	sail	15	1.69	0.48	2.01	0.85	1.54
Transparent	blender	blend	5	1.86	0.70	1.36	0.30	1.12
Transparent	stalker	stalk	5	1.90	0.70	0.70	0.00	1.62
Transparent	insistent	insist	0	1.96	0.78	1.90	0.70	1.77
Transparent	loafer	loaf	4	1.97	0.78	0.00	0.00	2.31
Transparent	wreckage	wreck	2	2.09	0.90	1.87	0.70	1.23
Transparent	hanger	hang	15	2.22	1.00	1.18	0.30	1.38
Transparent	boldness	bold	15	2.31	1.08	1.51	0.48	1.46
Transparent	locker	lock	16	2.36	1.15	1.96	0.78	1.62
Transparent	bearable	bear	20	2.52	1.30	1.63	0.48	1.23
Transparent	package	pack	16	2.52	1.30	2.45	1.23	2.00
Transparent	printer	print	3	2.58	1.36	1.83	0.70	1.35
Transparent	marcher	march	5	2.58	1.36	0.48	0.00	1.27
Transparent	painter	paint	8	2.71	1.46	2.52	1.28	1.31
Transparent	buyer	buy	10	2.75	1.51	1.86	0.70	3.46
Transparent	reader	read	15	2.77	1.52	2.76	1.52	1.50
Transparent	magical	magic	1	2.83	1.58	2.37	1.15	1.23

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Transparent	shipment	ship	11	2.90	1.65	1.38	0.30	1.58
Transparent	coolant	cool	12	2.91	1.65	0.85	0.00	2.08
Transparent	coverage	cover	13	3.01	1.77	2.29	1.08	1.65
Transparent	holder	hold	14	3.03	1.79	1.97	0.78	1.42
Transparent	leader	lead	15	3.10	1.85	3.09	1.84	1.23
Transparent	starter	start	6	3.20	1.95	1.86	0.70	2.04
Transparent	actor	act	9	3.41	2.16	2.90	1.65	1.19
Transparent	player	play	6	3.44	2.18	2.72	1.48	1.38
Transparent	backer	back	18	4.34	3.09	1.11	0.30	2.85
Transparent	scalding	scald	5	0.48	0.00	1.57	0.60	1.81
Transparent	mourner	mourn	1	1.04	0.30	0.90	0.00	2.16
Transparent	inhibitory	inhibit	1	1.26	0.30	0.78	0.00	1.12
Transparent	reaction	react	1	1.79	0.60	2.98	1.73	1.15
Transparent	adopted	adopt	2	1.95	0.78	2.05	0.85	2.00
Transparent	baronet	baron	6	2.03	0.85	1.04	0.30	2.15
Transparent	bulbous	bulb	2	2.07	0.85	1.48	0.48	3.60
Transparent	angelic	angel	2	2.29	1.08	1.57	0.48	1.23
Transparent	gloomy	gloom	2	2.29	1.08	2.26	1.04	1.31
Transparent	teacher	teach	5	2.36	1.15	3.15	1.90	1.38
Transparent	legendary	legend	0	2.40	1.18	2.08	0.90	3.62
Transparent	acreage	acre	3	2.43	1.20	1.51	0.48	1.12
Transparent	poetry	poet	5	2.49	1.26	2.58	1.34	1.23
Transparent	acidic	acid	3	2.59	1.34	1.20	0.30	1.31
Transparent	oxygenate	oxygen	0	2.61	1.38	0.00	0.00	2.54
Transparent	golfer	golf	4	2.74	1.49	1.71	0.60	1.96
Transparent	creamy	cream	3	2.75	1.52	1.88	0.70	1.58
Transparent	dreamer	dream	4	2.96	1.71	1.45	0.48	2.00
Transparent	fleshy	flesh	3	2.97	1.72	1.87	0.70	1.65
Transparent	soften	soft	5	3.14	1.90	1.26	0.30	1.50
Transparent	northern	north	2	3.21	1.96	2.98	1.73	1.38

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Transparent	viewer	view	3	3.58	2.33	1.63	0.48	1.31
Transparent	poacher	poach	6	0.70	0.00	1.30	0.30	1.38
Transparent	professor	profess	2	0.70	0.00	3.14	1.89	1.62
Transparent	welder	weld	11	1.08	0.00	1.08	0.30	1.54
Transparent	medical	medic	1	1.11	0.30	3.14	1.89	1.35
Transparent	binder	bind	15	1.56	0.48	1.23	0.30	1.31
Transparent	verbal	verb	7	1.63	0.48	2.35	1.11	1.27
Transparent	lender	lend	17	1.75	0.60	0.95	0.00	1.38
Transparent	looter	loot	16	1.83	0.70	0.00	0.00	1.76
Transparent	zealous	zeal	11	1.94	0.78	1.38	0.30	1.15
Transparent	herbal	herb	7	1.94	0.78	1.59	0.48	2.50
Transparent	singer	sing	16	2.01	0.85	2.12	0.90	1.42
Transparent	leakage	leak	12	2.05	0.85	1.32	0.30	1.15
Transparent	knocker	knock	1	2.28	1.04	1.40	0.30	1.73
Transparent	raider	raid	8	2.29	1.04	1.34	0.30	1.31
Transparent	hunter	hunt	11	2.40	1.18	2.31	1.08	1.84
Transparent	validity	valid	1	2.44	1.20	2.09	0.90	2.15
Transparent	pitcher	pitch	9	2.52	1.30	1.40	0.30	2.58
Transparent	climber	climb	1	2.52	1.30	1.91	0.70	1.23
Transparent	allowance	allow	3	2.60	1.36	2.51	1.28	1.12
Transparent	portable	port	14	2.64	1.40	2.09	0.90	1.31
Transparent	speaker	speak	4	2.76	1.52	2.49	1.26	1.38
Transparent	bandage	band	16	2.76	1.52	1.83	0.70	2.81
Transparent	renter	rent	17	2.84	1.59	0.48	0.00	2.15
Transparent	boxer	box	16	2.85	1.60	2.09	0.90	1.12
Transparent	claimant	claim	1	2.91	1.66	1.23	0.30	1.46
Transparent	breakage	break	6	2.91	1.67	1.18	0.30	1.19
Transparent	walker	walk	9	3.05	1.80	2.33	1.11	1.19
Transparent	payment	pay	27	3.06	1.82	2.64	1.40	1.27
Transparent	talker	talk	11	3.24	1.99	1.56	0.48	1.35

Stimulus type	Word	Stem	Neighborhood size	Log freq of stem	Log freq of stem (per million)	Log freq of word	Log freq of word (per million)	Transparency rating [a]
Transparent	finder	find	15	3.37	2.11	1.00	0.30	1.23
Transparent	clearance	clear	2	3.61	2.36	2.03	0.85	1.31
Transparent	childish	child	3	3.88	2.63	2.38	1.15	1.50
Transparent	eruption	erupt	0	0.78	0.00	1.67	0.60	1.35
Transparent	fizzle	fizz	2	1.00	0.00	0.00	0.00	1.19
Transparent	tufted	tuft	2	1.46	0.48	1.11	0.30	1.23
Transparent	nymphet	nymph	1	1.74	0.60	1.77	0.60	1.48
Transparent	filthy	filth	4	2.00	0.85	2.30	1.08	1.15
Transparent	employer	employ	0	2.02	0.85	2.66	1.41	1.00
Transparent	chilly	chill	4	2.26	1.04	1.99	0.78	1.58
Transparent	floater	float	3	2.29	1.08	1.32	0.30	1.23
Transparent	marshy	marsh	2	2.33	1.11	1.38	0.30	1.38
Transparent	critical	critic	0	2.34	1.11	2.90	1.65	1.12
Transparent	toaster	toast	3	2.40	1.18	1.08	0.30	1.23
Transparent	widowed	widow	0	2.41	1.18	1.76	0.60	1.27
Transparent	alarming	alarm	0	2.54	1.32	2.30	1.08	1.19
Transparent	agreement	agree	0	2.56	1.32	3.02	1.77	1.15
Transparent	bomber	bomb	4	2.71	1.48	1.71	0.60	1.40
Transparent	cloudless	cloud	2	2.73	1.49	1.40	0.30	1.42
Transparent	guilty	guilt	4	2.82	1.57	2.96	1.72	1.27
Transparent	drunkard	drunk	4	2.82	1.58	1.20	0.30	1.65
Transparent	dietary	diet	9	2.98	1.74	2.02	0.85	1.31
Transparent	risky	risk	7	3.02	1.78	2.02	0.85	1.08
Transparent	bloody	blood	4	3.40	2.15	3.06	1.81	1.62
Transparent	greenery	green	5	3.42	2.17	1.63	0.48	1.42

[a] On a scale from 1 (*semantically related*) to 5 (*semantically unrelated*).