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Evidence for Early Morphological Decomposition: Combining Masked Priming with Magnetoencephalography

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Abstract

Are words stored as morphologically structured representations? If so, when during word recognition are morphological pieces accessed? Recent masked priming studies support models that assume early decomposition of (potentially) morphologically complex words. The electrophysiological evidence, however, is inconsistent. We combined masked morphological priming with magneto-encephalography (MEG), a technique particularly adept at indexing processes involved in lexical access. The latency of an MEG component peaking, on average, 220 msec post-onset of the target in left occipito-temporal brain regions was found to be sensitive to the morphological prime–target relationship under masked priming conditions in a visual lexical decision task. Shorter latencies for related than unrelated conditions were observed both for semantically transparent (cleaner–CLEAN) and opaque (corner–CORN) prime–target pairs, but not for prime–target pairs with only an orthographic relationship (brothel–BROTH). These effects are likely to reflect a prelexical level of processing where form-based representations of stems and affixes are represented and are in contrast to models positing no morphological structure in lexical representations. Moreover, we present data regarding the transitional probability from stem to affix in a post hoc comparison, which suggests that this factor may modulate early morphological decomposition, particularly for opaque words. The timing of a robust MEG component sensitive to the morphological relatedness of prime–target pairs can be used to further understand the neural substrates and the time course of lexical processing.

INTRODUCTION

The nature of the representation of morphologically complex words has been a hotly debated issue in psycho-linguistics and more recently in the cognitive neuroscience of language (Marslen-Wilson & Tyler, 2007; Devlin, Jamison, Matthews, & Gonnerman, 2004). Understanding the nature of lexical representations has important implications not only for linguistic theories but also for the processing algorithms hypothesized to account for how humans make contact with lexical representations in real-time language comprehension. Are

morphologically complex words stored in terms of their putative parts (i.e., as separate meaningful units, morphemes; for example, add, add + ition, add + ed; Taft, 1979, 2004), or are they stored as full forms (Butterworth, 1983)? Is the language system built from a monolithic network in which morphological effects are only illusory, arising from similarities across ortho-graphically, phonologically, and semantically related items (Bybee & McClelland, 2005; Hay & Baayen, 2005; Seidenberg & Gonnerman, 2000; Bybee & Slobin, 1982)? Theoretically well-motivated and experimentally supported answers to these questions have important implications for our understanding of the basic elements of storage and computation in speakers' minds/brains. Moreover, whether linguistic organization arises from combining richly structured units of representation or emerges from statistical regularities over network associations has been a longstanding debate in psycholinguistics in particular but has also played out in cognitive science more generally (Pinker & Prince, 1988; Rumelhart & McClelland, 1986). Consequently, understanding the morphological computations involved in word recognition provides an inroad to better understand the fundamental computations employed by the brain. The current study provides electrophysiological evidence for internally structured lexical representations by combining data from magneto-encephalography (MEG; Hari, Levänen, & Raij, 2000; Lounasmaa, Hämäläinen, Hari, & Salmelin, 1996) and masked priming, a behavioral technique shown to be sensitive to morphological structure (Järvikivi, Pykkönen, & Niemi, 2009; Kazanina, Dukova-Zheleva, Geber, Kharlamov, & Tonciulescu, 2008; Duñabeitia, Perea, & Carreiras, 2007; Feldman, Soltano, Pastizzo, & Francis, 2004; Rastle, Davis, & New, 2004; Longtin, Segui, & Hallé, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000).

Models of morphological processing vary widely in their assumptions regarding the representational content of lexical items and their role in the processing system, ranging from full, across-the-board decomposition for all morphologically complex words (Stockall & Marantz, 2006; Taft, 1979, 2004) to postulating no role for morphemic representations (Plaut & Gonnerman, 2000). More specifically, morpheme-based accounts differ with regard to whether the hypothesized decomposition occurs early, at a prelexical or word-form level (sublexical models; see, e.g., Taft, 2004; Taft & Forster, 1975), or late, at a level where modality-independent (lexical) representations are accessed (supralexical models; e.g., Giraudo & Grainger, 2000, 2001). Parallel dual route models (Baayen, Dijkstra, & Schreuder, 1997; Schreuder & Baayen, 1995; Niemi, Laine, & Tuominen, 1994; Caramazza, 1988; Caramazza, Laudanna, & Romani, 1988) assume that both decomposed and full-form representations may be activated early, and the primary route used is dependent upon a variety of factors (e.g., the frequency of occurrence of the complex word form, etc.). With regard to the present study, these models can be divided into three groups: (1) those that incorporate early decomposition (full decomposition and parallel dual routes models; Stockall & Marantz, 2006; Taft, 2004; Schreuder & Baayen, 1995; Niemi et al., 1994; Caramazza, 1988; Caramazza et al., 1988), (2) those that support late decomposition (supralexical model; Giraudo & Grainger, 2000, 2001), and (3) connectionist models (Bybee & McClelland, 2005; Plaut & Gonnerman, 2000), wherein morphological structure is an emerging property, and “morphological” effects reflect the orthographic (or phonological) and semantic similarities between related words.

Masked priming has proven to be a powerful psycho-linguistic tool in assessing lexical processes and representation (Forster, 1998; Forster & Davis, 1984). In a typical masked priming experiment, participants execute a lexical decision task on visually presented target words that are preceded by briefly presented visual primes (e.g., <60 msec). A mask (e.g., “#####”) precedes the prime. The presence of a mask and the brief prime duration make the primes unavailable for report, and priming effects are assumed to be sensitive to early, automatic stages of lexical access. In overt priming designs, such as cross-modal priming (Marslen-Wilson, Tyler, Waksler, & Older, 1994), primes are consciously processed and can be assumed to reflect all (even the more central semantic) stages involved in recognizing a word. Interestingly, different patterns of priming effects have been observed in these two types of priming paradigms, reflecting the special emphasis they place on the different processing levels involved in lexical access. A basic finding in morphological priming studies is that targets that are morphologically related to their primes and, thus, share form and meaning (e.g., builder–BUILD), trigger faster RTs than targets preceded by unrelated primes. This semantically transparent prime–target relationship has elicited effects in studies using both masked (Rastle et al., 2000, 2004) and overt priming (Rastle et al., 2000; Marslen-Wilson et al., 1994) and has often been taken to reflect access to common stem representations and, thus, indicate morpheme-based access for morphologically complex words. On the other hand, semantically opaque prime–target relationships with only an apparent morphological relationship (e.g., corner– CORN) have not been found to speed up the processing of the target in overt priming (Meunier & Longtin, 2007; Rastle et al., 2000), suggesting that, at more central levels of processing, common representations have not been accessed. Here, the stem of the prime is only orthographically related to the target, yet the prime can be formally segmented into an existing stem and suffix. Interestingly, such semantically opaque complex words prime their targets’ stems in masked priming (Rastle & Davis, 2008; Rastle et al., 2000, 2004; Longtin et al., 2003). These masked priming results suggest early, automatic segmentation into morphemic representations. Moreover, this early decomposition is purely formal and blind to semantic properties, and it is, therefore, assumed to occur at a prelexical level. Crucially, in the orthographic priming condition (e.g., freeze–FREE), where prime and target share only ortho-graphic characters but the prime does not include an ending that is formally an existing suffix, no differences between unrelated and related conditions have been observed, even in masked priming (e.g., Marslen-Wilson, Bozic, & Randall, 2008; Rastle et al., 2004). This finding indicates that it is not just the orthographic overlap between the prime and target that yields the morphological priming effects. In other words, the orthographic and semantic similarities between morphologically related words, which are the predicting factors in connectionist accounts, cannot explain the morphological priming effects found in these masked morphological priming experiments. Moreover, the data suggest that morpheme-based representations are activated early in visual word recognition (Rastle & Davis, 2008), a result compatible with models assuming early, as opposed to late, decomposition.

Behavioral masked priming provides only an endpoint measure of the word recognition process. To obtain better temporal information, combining this behavioral task with electrophysiological methods can provide additional information about the subroutines involved in lexical access. This approach can help us better understand the time course of

the effects observed in masked priming and the nature of the accessed representations. Three studies using EEG combined with masked morphological priming have recently been reported (Morris, Grainger, & Holcomb, 2008; Lavric, Clapp, & Rastle, 2007; Morris, Frank, Grainger, & Holcomb, 2007), but the picture remains inconsistent. These ERP data have generally shown smaller amplitudes for related compared with unrelated conditions, at roughly 200–500 msec after the presentation of the target word, but the specific pattern of results for different conditions varies. In Morris et al. (2007), target words were preceded by primes with a 50-msec duration, followed by a 20-msec backward mask. They found significant behavioral priming effects (shorter RTs in the related than unrelated condition) for the transparent condition (e.g., farmer–FARM), smaller effects in the opaque condition (e.g., corner–CORN), and the smallest effects in the orthographic condition (e.g., scandal–SCAN). Similarly, in the ERP data, they observed a linear trend such that the semantically transparent condition showed the largest differences in amplitude of the N250 component between related and unrelated conditions and the orthographic condition the smallest. In the later N400 time-window, a priming effect was found only for the transparent condition. The gradual pattern at the N250, a component that has earlier been associated with prelexical processing (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006), was interpreted to reflect interactions between prelexical and semantic processing. The authors argue that the data, thus, support neither the prelexical decomposition account nor the original supralexical model (Giraudo & Grainger, 2001) but could be explained by a more interactive account that does not need to posit the existence of explicit morphological representations.

In contrast to Morris et al. (2007), Lavric et al. (2007) obtained results more consistent with the earlier behavioral masked priming effects found by Rastle et al. (2004) and Longtin et al. (2003). In a forward masked priming paradigm (i.e., no backward mask) with a prime duration of 42 msec, they found priming effects for the transparent and opaque conditions in the 340–500 msec time-window. For the orthographic condition, a reliable attenuation of the N400 was present only between 380 and 460 msec, suggesting that differences in the orthographic condition develop later and are more evanescent than differences found in the transparent and opaque conditions. This result was interpreted to support early orthography-based morphemic segmentation, in line with previous behavioral observations. However, in an earlier time-window (220–260 msec), there were topographical differences between groups: The transparent and orthographic conditions differed from each other, but the opaque condition was not reliably different from either the transparent or orthographic conditions, a pattern that is inconsistent with the typical behavioral findings.

In another study, Morris et al. (2008) found that in the early phase of the N250, the transparent and opaque conditions patterned together, and both were reliably different from the orthographic condition. This finding is interpreted as support for prelexical decomposition and is consistent with the original explanation for masked morphological priming whereby an early morphological parse of the visual input is conducted without reference to semantic features (Rastle & Davis, 2008; Rastle et al., 2004). In the later phase of the N250, the transparent and orthographic conditions patterned together, and both were reliably different from the opaque condition. Morris et al. (2008) suggested that this could arise from an early influence of semantic information, which would single out the opaque

condition, the condition where a purported morphological decomposition took place when it should not have.

Because of these contrasting ERP results—in particular, the differences in the early components between the findings in Morris et al. (2008) and Lavric et al. (2007)—the temporal nature of early decomposition and its electro-physiological correlates remains unresolved. We investigate whether more clear-cut electrophysiological evidence for internally structured early representations can be found using MEG, a technique that has not yet been employed in studying effects of masked morphological priming. MEG may be particularly suited for this purpose, as it has been argued to be sensitive to lexical properties and useful in distinguishing levels of lexical processing (Pykkänen & Marantz, 2003). The peaks in the MEG signal are likely to reflect less overlapping neural generators than those in the EEG, and the within-subjects nature of MEG can also be assumed to improve the sensitivity of observing small latency differences between conditions, as opposed to EEG, where grand averages are often employed. A recent study (Monahan, Fiorentino, & Poeppel, 2008) showed that masked priming and MEG can be effectively combined. They did not manipulate morphological structure but used identical words (VIDEO–video) as primes and targets. The latency of a component peaking roughly 225 msec after the presentation of the target word was sensitive to repetition and could, thus, be reflecting access to early lexical or pre-lexical representations. Their data suggest that MEG is a promising method for probing the nature of early lexical access with masked priming and offers specific hypotheses concerning the masked morphological priming investigated in the present study: Following earlier behavioral studies on masked morphological priming (Rastle et al., 2004; Longtin et al., 2003), we predicted that this peak (~225 msec) would show earlier latencies for the related than unrelated condition when the prime–target relationship is semantically transparent as well as when it is opaque but not when the prime and the target are only orthographically related.

Adding a new analytic wrinkle, we also studied whether possible priming effects at the 225-msec peak are sensitive to the lemma transitional probability (TP) of the morphologically complex primes, that is, the conditional probability of encountering a particular word form given its stem. The relative frequency between the complex word form and its stem has been suggested to affect the ease or difficulty of decomposition (Hay, 2001), and recent MEG studies by Lewis, Solomyak, and Marantz (2011) and Solomyak and Marantz (2010) found that the left hemisphere M170 component, which may be related to the present peak, was sensitive to this factor in visual recognition of morphologically complex and pseudocomplex words. We, thus, explored whether the assumed ease or difficulty with which decomposition takes place for the primes affects behavioral and MEG responses.

METHODS

Participants

Sixteen right-handed monolingual native speakers of American English (12 women; mean age = 22.6 years, $SD = 5.3$) with normal or corrected-to-normal vision participated in the experiment. Participants provided written informed consent and were compensated \$10/hr. Each experimental session lasted approximately 1.5–2 hr.

Materials

The stimulus materials used (targets, fillers, and pseudo-words) were the same as those employed in Rastle et al. (2004). The words were taken from the CELEX lexical database and consisted of 50 prime–target pairs per condition. In the *transparent* condition, the related primes had a morphological and semantically transparent relationship with the target (e.g., alarming–ALARM). In the *opaque* condition, the related primes had an only apparent morphological relationship with the target but no semantic relationship (e.g., department–DEPART).¹ The related primes in the *orthographic* condition, in turn, bore no apparent morphological or semantic relationship with the target, only an orthographic relationship (e.g., demonstrate–DEMON). The primes in the transparent and opaque conditions could be (if only apparently) parsed into two existing morphemes, a stem and a suffix, whereas the endings in the orthographic primes were not real morphemes. The primes and the targets were matched across conditions for target frequency, prime frequency, target neighborhood size, target length, target family size, and orthographic overlap. According to semantic relatedness values (Latent Semantic Analysis; Landauer & Dumais, 1997), the prime–target pairs in the transparent condition were significantly more related semantically than in the opaque and orthographic conditions, which, in turn, did not differ from each other in terms of the semantic relatedness (see Rastle et al., 2004, for a statistical summary of the stimulus characteristics). For the target words in each condition, the stimulus set also included unrelated prime words that were matched for length to the related prime words. These primes were morphologically complex (suffixed) words that were not semantically, morphologically, or orthographically related to the targets.

In addition to the actual target conditions with related and unrelated primes, 50 unrelated prime–target pairs were included to reduce the relatedness proportion to 0.37. The primes in this filler group were suffixed words, and the target words were matched for length to the other targets. Additionally, two hundred pseudowords, matched for length to the real word targets, were included. These items were paired with real suffixed prime words.

The stimuli were divided into two blocks. Because MEG is better suited for within-subjects design, target words were presented twice (once preceded by a related prime, once by an unrelated prime) to participants, but always in different blocks. Presentation order was counterbalanced across participants. The items were divided into the blocks such that half of the items from each condition had related primes and half had unrelated primes in one block, and thus, there was an equal number of items of each stimulus pair type (e.g., related orthographic, unrelated orthographic, related opaque, etc.) in each block. The presentation order of the items within each list was randomized separately for each participant.

For the TP analyses, all words that contained the stem of each prime word in the morphological groups (transparent and opaque; related and unrelated) were searched from the WebCelex database (Max Planck Institute for Psycholinguistics, 2001), and their individual frequencies were summed together to obtain the cumulative stem frequency for each prime word (compound words where the stem in question was not the first constituent

¹The Rastle et al. stimuli included both “pseudomorphological” word pairs, such as *corner–corn*, as well as truly semantically opaque prime–target relationships, e.g., *archer–arch*.

were excluded from these sums). The surface frequencies of the actual prime word forms were also collected. In line with Solomyak and Marantz (2010), the lemma TP was defined as the ratio of each word's surface frequency to its cumulative stem frequency (lemma frequency). The prime words in both morphologically related groups as well as in their control groups were all divided into two bins according to their TP values (high vs. low; for transparent high: mean TP value = 0.351, range = 0.110–0.837; transparent low: mean = 0.034, range = 0.002–0.088; opaque high: mean = 0.425, range = 0.130–0.758; opaque low: mean = 0.054, range = 0.002–0.127), yielding altogether eight lists of words (25 items in each).

Procedure

Participants lay supine in a dimly lit, magnetically shielded room and viewed stimuli presented on a screen at a distance of approximately 37 cm from their eyes. The stimuli were presented using DMDX (Forster & Forster, 2003). The structure of each trial is depicted in Figure 1. First, a mask (i.e., “#####”) was presented for 500 msec, immediately followed by the prime, presented in lower case for 39 msec. The prime was immediately followed by the target word in upper case. Participants performed a lexical decision on the target word, which disappeared when the participant made a response. The change in case from the prime to the target was to ensure that the stimuli were physically distinct and required access to an appropriate (likely linguistic) representation. The intertrial interval pseudorandomly varied between 400 and 759 msec. Items were presented in Courier New font, in which upper and lower case items are visually distinct and in which all characters occupy the same amount of space horizontally irrespective of the shape of the letter. The text was shown in yellow on a black background (visual angle = 0.67° horizontal and vertical per character; 2.83° horizontal per average word). Participants were instructed to decide as quickly and accurately as possible whether the letter string was a real word or not. They were not informed of the presence of the primes before the end of the experiment. Neuromagnetic signals were measured using a 160-channel whole-head axial-gradiometer MEG system (Kanazawa Institute of Technology, Japan). Data were recorded at a sampling rate of 500 Hz (recording bandwidth DC to 100 Hz, low-pass filter; 60 Hz on-line notch filter). Structural MRIs were not available for our participants. Consequently, each participant's head shape was digitally recorded before MEG measurement. The head shapes were later used to estimate the spherical head models used for source localization. Electrodes were placed at five fiducial points providing a 3-D coordinate system for each participant and to estimate the head position in the MEG scanner relative to the sensors.

Data Analysis

Noise reduction was performed on the MEG data using a multi-time shift PCA noise reduction algorithm (de Cheveigné & Simon, 2007, 2008a, 2008b). Subsequent to applying the noise reduction algorithm on the acquired data, visual inspection was conducted to remove any remaining trials with obvious artifacts (deviations greater than ± 2.5 pT criterion). The data were averaged per condition, after removing incorrect trials or those associated with response times 2.5 times the standard deviation (*SD*) above or below the individual condition mean value (9.53% of the trials). Off-line filtering (digital band pass filter with a Hamming window; range = 0.03–14 Hz) and baseline correction (250 msec

epoch before the prime) were then performed on the averaged data. A robust peak was observed across participants and conditions at approximately 220 msec in the left hemisphere and at about 210 msec in the right hemisphere after presentation of the target word (see Figure 2). The magnetic field contour of the peak (Figure 3) resembled a typical M170 contour elicited by written words (see, e.g., Harris, Pylkkänen, McElree, & Frisson, 2008; Fiorentino & Poeppel, 2007; Stockall, Stringfellow, & Marantz, 2004; Pylkkänen & Marantz, 2003), that is, an outgoing magnetic field in the left posterior sensors and an incoming field in the right posterior sensors. This peak, as predicted, was exceptionally similar in timing, distribution, and magnetic field contour to that reported in Monahan et al. (2008). Ten channels with the strongest magnetic field were selected separately for each participant from only the source (outgoing magnetic field) of this component in the left hemisphere for quantitative analyses, given that the sink (ingoing magnetic field) was not clearly visible across participants due to limitations of the sensor configuration as well as subjects' head position in the scanner. Similarly in the right hemisphere, 10 channels with the strongest magnetic field from the sink (as the source was not visible) were selected for separate analyses. The sensor data were analyzed at the magnetic field peak for each individual, and the same individually selected sensors were employed for all conditions for that participant. The peak latency and amplitude of this component (~220 msec post-onset of the target) in the root mean square (RMS) of the MEG temporal waveform were carried forward for statistical analysis. The TP analyses were performed for the eight lists of interest in a similar fashion but only in the left hemisphere (because the right hemisphere analyses did not yield significant effects in our primary comparisons).

In line with previous experiments that combined MEG with masked priming (Monahan et al., 2008), no consistent pattern of peaks was observed across all participants in later time-windows beyond the component peaking at about 220 msec. We nevertheless investigated whether the prime–target relationship had any effects on possible M350 latencies, as could be hypothesized on the basis of earlier MEG studies, albeit without masked priming (e.g., Pylkkänen, Llinas, & Murphy, 2006; Pylkkänen & Marantz, 2003). Moreover, Lavric et al. (2007) and Morris et al. (2007) found priming effects in the N400 time-window. We, thus, analyzed the first left hemisphere peak that had an M350-type magnetic field distribution between 300 and 600 msec (mean latency of these peaks = 374 msec).² Five channels from the source and five from the sink were selected individually for each participant for the analyses. Additionally, we analyzed the average RMS amplitudes for each condition within the time-window of 300–600 msec, as well as in the 250–450 msec and 450–600 msec time-windows. The channels (five from the source and five from the sink) were selected according to the highest peak in the left hemisphere in the 250–600 msec time-window. To investigate whether the TP factor would play a role in later time-windows, the average RMS amplitudes were analyzed in these same time-windows for the eight TP lists.

²One participant did not show an M350-type distribution for any of the peaks within this time range and was excluded from the late time-window analyses.

Source Modeling

Before dipole source localization, participants' digitized head shapes were projected onto a standardized brain. Source modeling was done using BESA Research 5.3. (BESA GmbH, Munich, Germany), and its RAP music algorithm that assumes an independent topography source model allowing for synchronous sources. To localize the source(s) of the primary peak of interest, an ECD model was first fit to the 20-ms time-window before the peak (rising slope) for each participant's grand averaged data (across all six conditions). All sensors were used in localization. This model was then applied for all the individual conditions of that participant. Six subjects had to be excluded due to an unacceptable difference between head position coils or due to the localization not resulting in high-enough goodness-of-fit (GoF) in anatomically possible locations ($n = 10$ for ECD modeling). The GoF values for grand averaged data were above 80% in all the accepted participants (mean = 92.3%; for 7 of 10 participants, GoF > 90%). A bilateral dipole was best able to account for the activity in four of these participants, whereas a left hemisphere dipole was sufficient for others. Additionally, a second dipole was added to the model in 2 of 10 participants to account for the yet unexplained activity (for one subject, this was in the left hemisphere, for the other in the right).

RESULTS

Behavioral Results

None of the participants exceeded the preset error rate criterion of 15%. The individual error rates including all items (targets, fillers, pseudowords) varied between 1.63% and 12.5% (mean = 6.26%, $SD = 3.17$). The RTs and error rates for each condition are shown in Table 1. A two-way repeated measures ANOVA (with Greenhouse–Geisser correction) for Condition (three levels: ortho-graphic, opaque, transparent) and Relatedness (two levels: related, unrelated) was performed on the RT and accuracy data. For RTs, significant main effects for Condition ($F(2, 30) = 20.5, p < .001$) and Relatedness ($F(1, 15) = 33.8, p < .001$) were found, as well as a significant interaction between the two factors ($F(2, 30) = 6.55, p = .007$), indicating that priming effects differed across conditions. Direct comparisons of the magnitude of the priming effects (unrelated minus related; see Figure 4) between conditions revealed that the morphologically transparent condition did not differ from the morphologically opaque condition ($t(15) = 1.65, p = .120$) but did differ from the orthographic condition ($t(15) = 3.66, p = .002$), which showed the smallest amount of priming. The opaque versus orthographic difference was marginally significant ($t(15) = 2.10, p = .054$). The ANOVA for error rates showed a significant main effect for Condition ($F(2, 30) = 12.9, p < .001$) but did not show a significant main effect of Relatedness or an interaction. In short, the behavioral results replicate previous masked priming findings (Rastle & Davis, 2008; Rastle et al., 2004).³

For the TP analyses, a three-way repeated measures ANOVA (with Greenhouse–Geisser correction) for the factors Condition (two levels: transparent, opaque), Relatedness (two levels: related, unrelated), and TP (two levels: high, low) was performed for the RT data. Significant main effects of Condition ($F(1, 15) = 14.6, p = .002$) and Relatedness ($F(1, 15) = 45.8, p < .001$) were found, as well as an interaction between TP and Condition ($F(1, 15) =$

17.2, $p = .001$). In addition, we found a close-to-significant three-way interaction between Condition, Relatedness, and TP ($F(1, 15) = 3.19, p = .094$), indicating that the priming effects for the different TP groups differed somewhat between the opaque versus transparent conditions. Direct contrasts (see Table 2 for RTs) revealed that the high TP opaque group did not show significant priming ($t(15) = 1.07, p = .303$) whereas all the other conditions did (low opaque, $t(15) = 2.58, p = .021$; high transparent, $t(15) = 6.97, p < .001$; low transparent, $t(15) = 2.87, p = .012$). In error rates (see Table 2), there were significant main effects of Condition ($F(1, 15) = 4.97, p = .041$) and of TP ($F(1, 15) = 28.8, p < .001$), and an interaction between TP and Condition ($F(1, 15) = 15.2, p < .001$), but no significant interactions with Relatedness. In direct contrasts, the only significant effect was the one observed with the low transparent group ($t(15) = 2.18, p = .045$).

MEG Results

ECD source locations were calculated for the 220-msec peak to show that its source was not a motor response related to the button press. Figure 5 depicts the sources of the peak that primarily localize to left (or bilateral) posterior occipital and temporal regions, similar to the sources that have been found for the M170 component (see, e.g., Pylkkänen & Okano, 2010; Harris et al., 2008; Pylkkänen et al., 2006; see also Gold & Rastle, 2007, for an fMRI study on masked morphological priming). The sources were more medial than expected (but see Pylkkänen et al., 2006), which is likely to be due to the model treating the observed source and sink pattern (see Figure 3) as arising from the same set of generators when all sensors are included in the analysis. Although we do not have structural MRIs of the participants, the gross dipole locations support the view that the peak is not related to motor activity. Source amplitudes and latencies were calculated for the highest peak between 150 and 300 msec separately in the left and right hemisphere dipoles, but no significant effects emerged, possibly because of lack of statistical power.

220-msec Peak Analysis

On the basis of Monahan et al.'s (2008) results, we predicted that the latency of the left hemisphere component peaking roughly 220 msec post-onset of the target would show priming effects when the prime–target relationship is semantically transparent as well as when it is opaque but not when the prime and the target are only orthographically related. For the peak latencies (see Table 3), a repeated measures ANOVA (Condition \times Relatedness; with Greenhouse–Geisser correction) showed a significant main effect of Relatedness ($F(1, 15) = 11.8, p = .004$) and an interaction between Relatedness and Condition ($F(2, 30) = 4.78, p = .016$), demonstrating that the priming effects differed across conditions. Direct comparisons for the magnitude of priming (unrelated minus related; see

³According to Marslen-Wilson, Bozic, and Randall (2008; see also Morris et al., 2008), the Rastle et al. (2004) stimuli include a potential confound, namely a differential number of phonologically mismatching prime–target pairs (e.g., *rabbit–rabbi*; *united–unit*) in different conditions. To examine a possible effect of this factor, we reanalyzed the behavioral data after removing such items, but the central effects remained the same. There was a significant main effect of relatedness ($F(1, 15) = 15.4, p = .001$) and of condition ($F(2, 30) = 23.2, p < .001$), as well as a significant interaction between the two factors ($F(2, 30) = 6.81, p = .004$), indicating differences in the magnitude of priming between conditions. Direct comparisons of the priming effects revealed that the orthographic condition did not show significant priming ($\text{priming} = 5$ msec) and differed significantly from the opaque condition ($\text{priming} = 22$ msec; $t(15) = 2.62, p = .019$) and from the transparent one ($\text{priming} = 31$ msec; $t(15) = 3.35, p = .004$), whereas the opaque and transparent conditions both continued to show a robust priming effect of similar magnitude ($t(15) = 1.24, p = .235$).

Figure 6) across conditions revealed that, as predicted, the transparent and opaque conditions showed significantly larger effects than the orthographic condition (transparent vs. orthographic, $t(15) = 2.13, p = .050$; opaque vs. orthographic, $t(15) = 3.05, p = .008$), but the magnitude of priming between the transparent and the opaque conditions did not differ ($t(15) = 0.70, p = .496$). For the peak amplitudes (see Table 3), we found only a significant main effect of Condition ($F(2, 30) = 3.80, p = .040$; lowest mean amplitudes for the opaque conditions) but no effect of Relatedness nor an interaction between Condition and Relatedness. Similar analyses for the right hemisphere peak (mean latency ~ 210 msec) yielded no significant effects (all p values > .100). In short, as predicted, the MEG results showed that the latency of the 220-msec peak in the left hemisphere was sensitive to the morphological relationship between the prime and the target (shorter latencies for morphologically related than unrelated conditions) but was not affected by a solely orthographic prime–target overlap (similar latencies for orthographically related and unrelated conditions).

Late Time-Window Analyses

No significant effects were observed in the analyses of the latencies or amplitudes of the first peak that had an M350-type field distribution (all p values > .100). The analysis of the average amplitudes in the 250- to 600-msec time-window revealed significant main effects of Relatedness ($F(1, 14) = 5.97, p = .028$) and Condition ($F(2, 28) = 5.36, p = .019$), but no interaction ($F(2, 28) = 0.08, p = .921$). Further analyses on the mean amplitudes of the earlier time-window between 250 and 450 msec showed that a main effect of Condition was observed ($F(2, 28) = 4.46, p = .030$), but only a close-to-significant effect of Relatedness ($F(1, 14) = 3.51, p = .082$) and no significant interaction between the two factors ($F(2, 28) = 0.22, p = .786$). In the later time-window at 450–600 msec, however, a significant main effect of Relatedness was observed ($F(1, 14) = 6.99, p = .019$) as well as a main effect of Condition ($F(2, 28) = 4.16, p = .033$), but the interaction between the two factors was not significant ($F(2, 28) = 0.96, p = .891$). This analysis indicates that the target words preceded by related primes elicited smaller amplitudes in this later time-window than words presented by unrelated primes, but the differences were similar across the different conditions. Because the effects are very late and did not differ across target conditions, we do not currently have an explanation for these findings.

TP Analyses

In the analyses for the TP factor on the latency of the 220-msec peak, a three-way (Condition \times Relatedness \times TP) repeated measures ANOVA revealed a significant main effect of Relatedness ($F(1, 15) = 4.63, p = .048$) and an interaction between Condition and Relatedness ($F(1, 15) = 5.58, p = .032$), suggesting that the morphological conditions (transparent versus opaque) differed in their priming effects. The three-way interaction was not significant ($F(1, 15) = 2.04, p = .173$), but direct comparisons revealed that only the low opaque TP group showed significant differences at this peak ($t(15) = 3.44, p = .004$), but not the high opaque TP group ($t(15) = 1.32, p = .205$) or the high ($t(15) = 0.61, p = .551$) or low ($t(15) = 0.041, p = .968$) transparent TP groups (see Table 4). There were no significant effects in the amplitude of this peak or any Relatedness \times Condition interactions in the average RMS amplitudes calculated for the later time-windows.

DISCUSSION

The aim of the present study was to investigate the nature of early morphological decomposition by combining masked priming with MEG, an electrophysiological technique that has been found to be useful in probing different levels of lexical processing. MEG has also been shown to be able to be effectively combined with masked priming (Monahan et al., 2008). To date, however, MEG has not been employed in the study of masked morphological priming. We hypothesized that the MEG temporal waveform might produce clearer results than previous EEG studies, where the effects have been, to some extent, inconsistent and observed over a large time-window (200–500 msec). Our primary effects are straightforward and consistent with previous behavioral studies on masked morphological priming. As predicted, the morphological prime–target relationship affected the latency of a left hemisphere MEG component peaking, on average, 220 msec post-onset of the target word, and these effects were not modulated by semantic transparency between the prime and target. Additionally, consistent with previous behavioral and electrophysiological results, significant effects were not observed when the prime and target were only orthographically related. This general pattern of results was also observed in the RT data. Our primary findings indicate that the morphological effects cannot be explained merely by orthographic or semantic similarity between the primes and the targets as connectionist models would assume (Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000) and are also in contrast with hypotheses put forward by supralexical models (Girardo & Grainger, 2000, 2001), which assume that morpheme-based representations are accessed only after whole-word representations. Instead, the current results are in line with models that incorporate early decomposition in their architecture.

In MEG, visually presented words typically elicit a multi-peak waveform, beginning from a low-level visual component peaking at approximately 100 msec (Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003; Tarkiainen, Cornelissen, & Salmelin, 2002) and a letter-string-sensitive M170 component (or “Type II activity” in Tarkiainen et al., 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999), followed by a peak between 200 and 300 msec (the so-called M250) and the M350 component that appears to be sensitive to properties affecting lexical access (Solomyak & Marantz, 2009; Beretta, Fiorentino, & Poeppel, 2005; Pylkkänen, Stringfellow, & Marantz, 2002). In the present study, which employed masked priming, the abovementioned waveform pattern was not observed: There was only one peak that was consistently observed across all participants and conditions, with an average peak latency of roughly 220 msec post-onset of the target. Yet, this pattern is consistent with the morphology of the MEG temporal waveform elicited in identity masked priming (Monahan et al., 2008), also with regard to the magnetic field distribution of the peak. Moreover, the fact that we did not observe any significant priming effects in the amplitude of this peak is consistent with previous MEG results. The magnetic field distribution is characteristic of that typically observed with the M170 component (e.g., Fiorentino & Poeppel, 2007; Stockall et al., 2004; Pylkkänen & Marantz, 2003), whereas the average latency is closer to that of the M250 component (see, e.g., Pylkkänen & Marantz, 2003). As the sources of this peak were localized to similar regions as are those of the M170 (e.g., Harris et al., 2008), the present peak may be an M170-related component. Another

possibility is that it is in some way specific to masked priming (consistent with the hypothesis that the N250 elicited in the EEG masked priming experiments is specific to the masked priming design; Grainger & Holcomb, 2009). Additional research is necessary to tease apart these possibilities.

Interestingly, priming was, to some extent, modulated by the TP of the stem and suffix of the primes, that is, the probability of encountering a particular suffix after a given stem. Both the high and low TP transparent groups as well as the low TP opaque group showed significant priming in their RTs, whereas the high TP opaque group did not. However, only the low TP opaque group showed effects in the 220-msec MEG response. It is, at this stage, unclear why the transparent items of the low and high TP groups did not show effects in the MEG responses but still in the RTs. Yet, it is interesting that the high opaque group did not show significant priming effects in either behavioral or MEG measures. The present data would, thus, preliminarily suggest that it might not be the case that all morphologically pseudocomplex (opaque) words are decomposed early and, therefore, prime their stems. According to Hay (2001), words with relatively high frequent surface forms in relation to the frequency of their stems (i.e., high TP words) are generally less likely to show effects of decomposition than words with lower TP values (which are relatively low frequent forms in the family of their stems). This is in contrast to the full, across-the-board decomposition view but is in line with dual-route models (e.g., Schreuder & Baayen, 1995), which assume that the early access to morphologically complex or pseudo-complex words may occur via decomposition, accessing full-form representations or both, depending on certain factors.

Solomyak and Marantz (2010) suggest that the reason Morris et al. (2007) found graded effects rather early in the ERP signal was not because of early influence from semantics but due to the fact that their stimuli were not matched for TP. Here, the high TP opaque items also had somewhat higher mean TP value than the high TP transparent group (0.42 vs. 0.35). However, the difference was not statistically significant ($p = .195$). It is questionable whether the difference observed here in the RT priming effects between these groups would be found solely because of these somewhat different TP values or whether semantic opacity also plays a distinct role. Yet, it should be noted that the present TP analysis was a post hoc comparison, and future research with items specifically controlled to study this issue is necessary to resolve this question.

Previous experiments using morphological priming with long prime durations (e.g., Rastle et al., 2000) or cross-modal priming (e.g., Meunier & Longtin, 2007; Marslen-Wilson et al., 1994) have typically shown clear effects of semantic transparency: Prime words that have a semantically opaque relationship to the target do not produce significant priming effects. As the primes are consciously perceived in these paradigms, these findings likely reflect an amodal, lexical level of representation. Sharing the same (orthographic and semantic) morpheme appears to be the source of the effect.⁴ Morphological effects in masked priming, in turn, indicate an earlier level of processing typically insensitive to semantic relationships but where purely form-based representations of stems and affixes are accessed (Rastle &

⁴It should be noted that morphological priming at this level has been distinguished from semantic priming (idea–notion) and, thus, has been proposed to constitute a different level of representation (e.g., Marslen-Wilson et al., 1994, 2008).

Davis, 2008). A study by Marslen-Wilson et al. (2008) confirms that masked morphological priming effects arise from an earlier segmentation stage and do not stem from activation of central lexical representations of the decomposed stems of the derived prime words. As semantic opacity did not play a role in our primary findings, priming effects in the peak latency of 220 msec that were observed in the present study are likely to reflect early form-based representations rather than more central lexical representations. Although our primary hypotheses concerned this earlier peak, we also found differences between related and unrelated prime–target pairs in all conditions in a very late time-window (450–600 msec). It is at this stage unclear what these late-stage effects might reflect, and additional research is required to explain these findings.

As described above, previous studies investigating masked morphological priming with EEG have produced somewhat inconsistent results. Effects roughly consistent with the majority of the behavioral masked priming literature (and the current MEG study) were, however, found in Lavric et al. (2007) in the N400 component (at 380–500 msec) and in the early phase of the N250 component (at 200–250 msec) in Morris et al. (2008). The timing of the latter result is consistent with the present findings, where we found a reliable difference at roughly 220 msec post-onset of the target word. The N250 is a component frequently elicited by masked priming in EEG, and it appears to be sensitive to sublexical properties (e.g., ortho-graphic and phonological overlap between the prime and the target; see Grainger & Holcomb, 2009). Morris et al. (2008) suggest that the N250 is composed of distinct subcomponents, the earlier phase reflecting prelexical ortho-graphic processing and the later phase reflecting prelexical phonological processing (see also Grainger, Kiyonaga, & Holcomb, 2006) or the earliest indications of semantic influence (Morris et al., 2007, 2008). This division could explain the differential effects observed in these two studies (Morris et al., 2007, 2008) as well as the early graded topography effect of Lavric et al. (2007). The latency and the suggested function of the early N250 component are, thus, consistent with the present findings in attributing our effects to prelexical morpho-orthographic decomposition.

Other single-word paradigms in the visual domain also provide evidence of early morphological decomposition. Laine, Vainio, and Hyönä (1999) used progressive de-masking, which emphasizes early stages of lexical access, and found an effect of morphology when they compared behavioral responses to morphologically complex versus monomorphemic Finnish nouns. Using simultaneous MEG and visual lexical decision, Fiorentino and Poeppel (2007) compared responses to compound words with high constituent frequencies (e.g., *flagship*) that were matched for surface frequency with monomorphemic single words (e.g., *crescent*). They found shorter M350 latencies for the compounds than matched monomorphemic words, reflecting the higher frequency of the morphological constituents. These results were taken to support the early decomposition of compounds. Because the M350 has been shown to be sensitive to properties affecting access to actual lexical representations (Solomyak & Marantz, 2009; Beretta et al., 2005; Pykkänen & Marantz, 2003; Pykkänen et al., 2002), it is likely that the effects of Fiorentino and Poeppel (2007) at the M350 reflect the more abstract, amodal representations

of morphemes and words, whereas effects observed in masked priming are reflecting an earlier, prelexical level of representation.

Using MEG, Zweig and Pykkänen (2009) investigated the influence of morphology on early word recognition by contrasting morphologically complex (derived) words (e.g., *farmer*, *refill*) directly with monomorphemic words (e.g., *switch*) and orthographic control words (e.g., *winter*, *reckon*) in a lexical decision task. They found complexity effects at the M170. These effects, however, were primarily found in the right hemisphere. Importantly, the ortho-graphic controls patterned with monomorphemic words, suggesting that both an existing stem and an affix are required for decomposition to take place. This pattern of results supports prelexical decomposition and is in line with the present findings (apart from the hemisphere difference), as well as previous masked priming results, which show that only an existing stem without a real suffix (such as in the orthographic condition) is not sufficient for the stem to be activated. Apart from Zweig and Pykkänen (2009), direct contrasts between visually presented morphologically complex and simple words in the standard visual lexical decision (without priming or other manipulations) have not usually found robust effects that could directly be attributed to early visual prelexical decomposition, neither behaviorally (Hyönä, Vainio, & Laine, 2002), nor in brain imaging (Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006) or electrophysiological measures (Leinonen et al., 2009; Vartiainen et al., 2009; Lehtonen et al., 2007). This is despite the fact that effects of morphological decomposition that are likely to correspond to a later lexical or semantic access stage (Leinonen et al., 2009; Vartiainen et al., 2009; Fiorentino & Poeppel, 2007; Lehtonen et al., 2006, 2007) and/or to the semantic-syntactic integration of morphemes (Leinonen et al., 2009; Vartiainen et al., 2009; Lehtonen et al., 2006, 2007) have been observed in these contrasts. This suggests that the early prelexical decomposition stage, although observable in a masked priming setting, may often be a rather fast and automatic process in normal circumstances. This observation emphasizes the usefulness of masked priming in studying these early visual word recognition processes and the nature of lexical representation.

In conclusion, we provide the first MEG evidence for effects of morphological complexity in masked priming. Priming effects for morphological prime–target relationships were observed in a component peaking at 220 msec post-onset of the visual target in the left hemisphere, as well as in the behavioral RT data. These effects were similar both for transparent and opaque prime–target relationships. The orthographic controls showed no effects at this component or in the behavioral data. In line with previous studies using masked priming, the effects likely reflect a prelexical level of processing where form-based representations of stems and affixes are represented. The findings challenge models that claim no role for morphological structure in lexical representations. Interestingly, the TP from the stem to the suffix seemed to modulate the priming effects to some extent, that is, semantically opaque prime words with high TP showed no significant priming, whereas low TP opaque words showed effects both in the RTs and in the MEG response. This finding, although preliminary, might suggest that not all semantically opaque words, in particular those that are relatively high-frequency forms in the family of their stems, are decomposed, a result consistent with dual route models. In general, the timing of a robust MEG component

was found to be sensitive to the morphological relatedness of prime–target pairs and can thus be used to further understand the neural substrates and the timeline of lexical processing, as well as the representational nature of lexical items.

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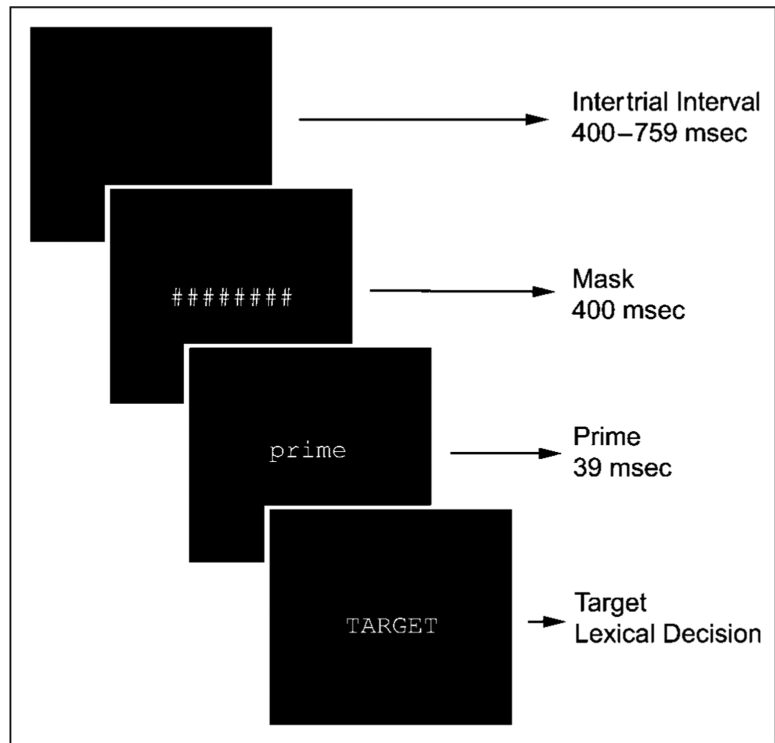


Figure 1. Trial structure. The mask remained on the screen for 400 msec, immediately followed by the prime for 39 msec, immediately followed by the target, which remained on the display until a lexical decision was made.

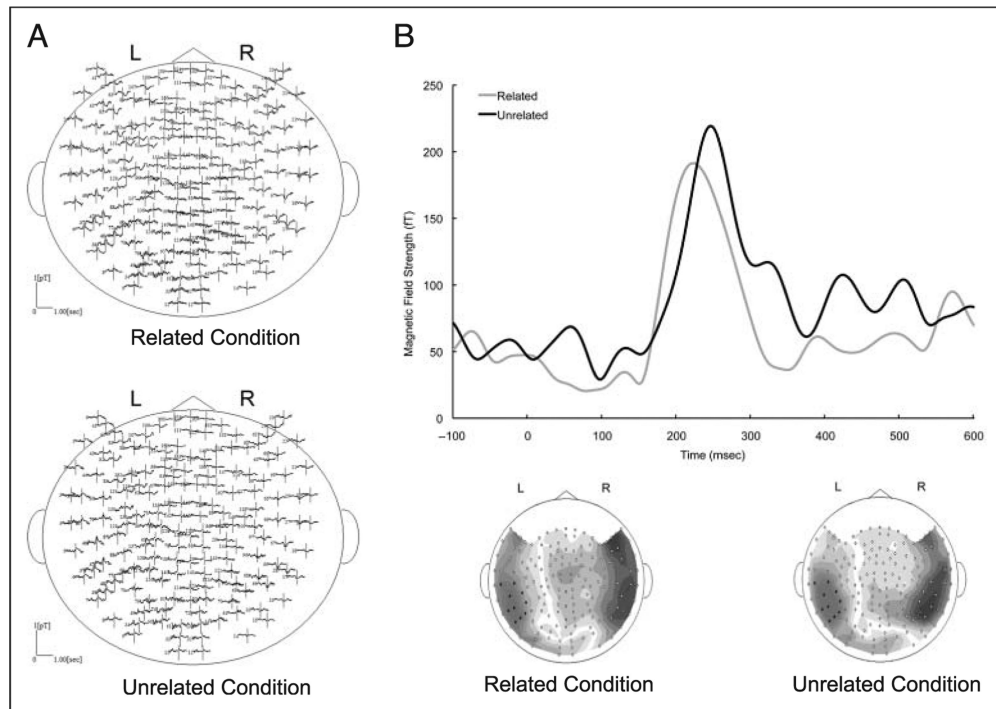


Figure 2.

(A) The MEG responses (–300–700 msec) in all channels for the transparent conditions (top, related condition; bottom, unrelated condition). Data are from a representative subject. (B) RMS waveform of the robust peak identified after the onset of the target. Time 0 indicates the onset of the target.

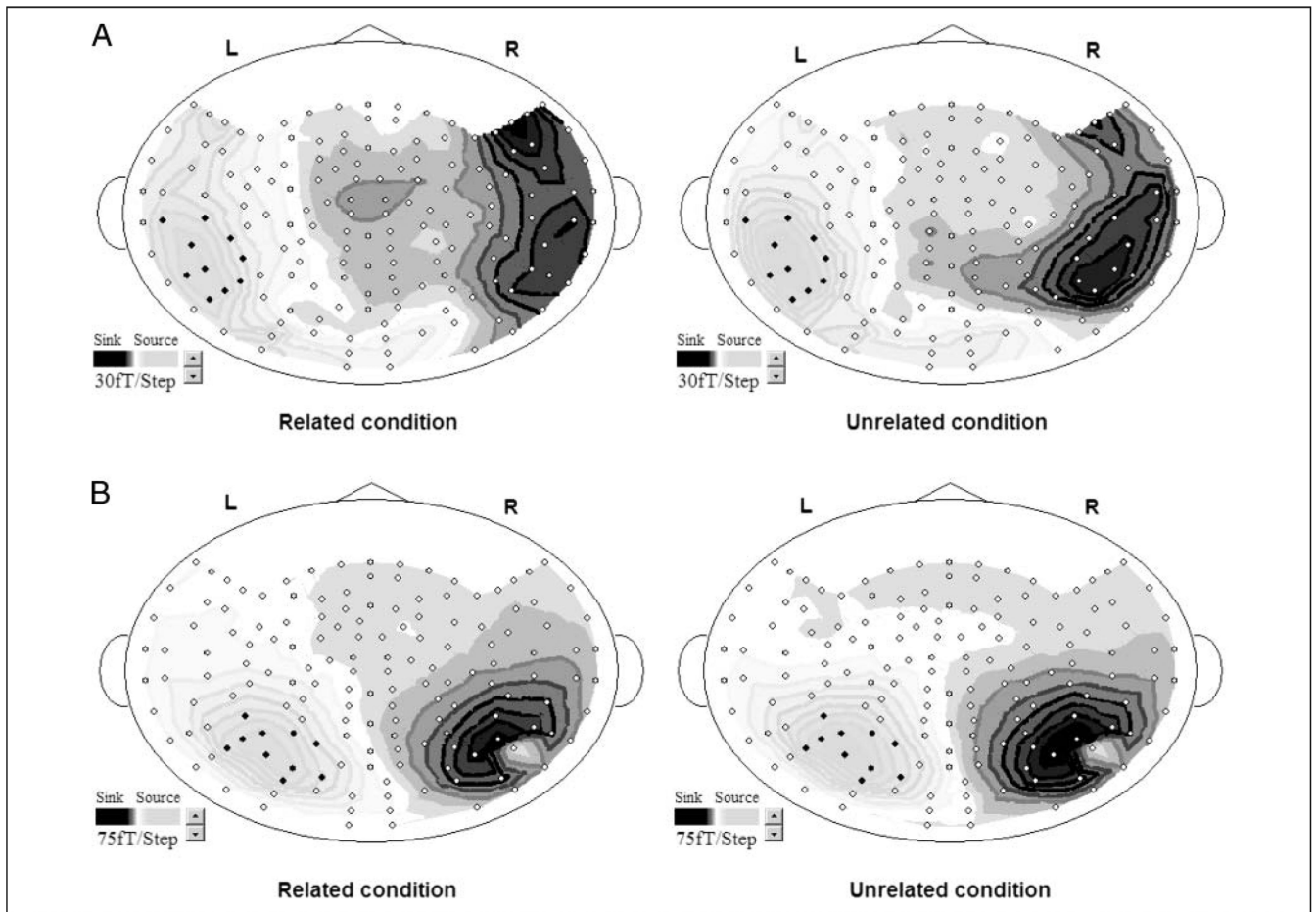


Figure 3.

The magnetic field distribution of the component peaking, on average, at 220 msec for the related and unrelated transparent conditions for two representative participants (A and B). Dark gray indicates an outgoing magnetic field (sink), whereas light gray indicates an incoming magnetic field (source); note that the visible source and the visible sink are not generated from the same dipole as they are in different hemispheres.

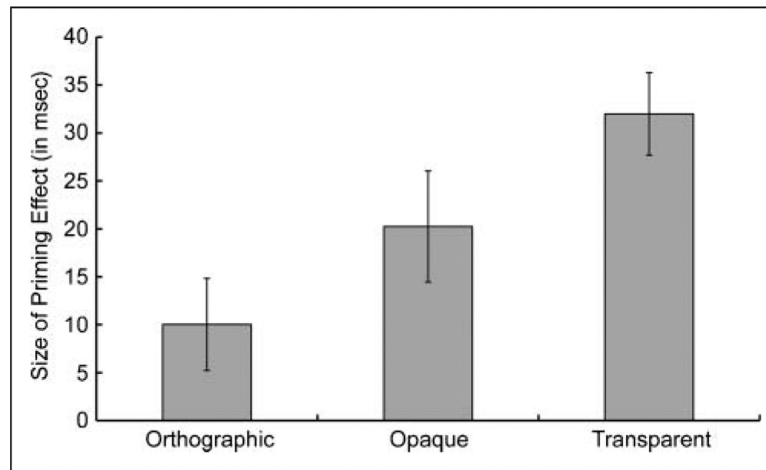


Figure 4. Magnitude of priming observed in the RTs for the different conditions (unrelated vs. related).

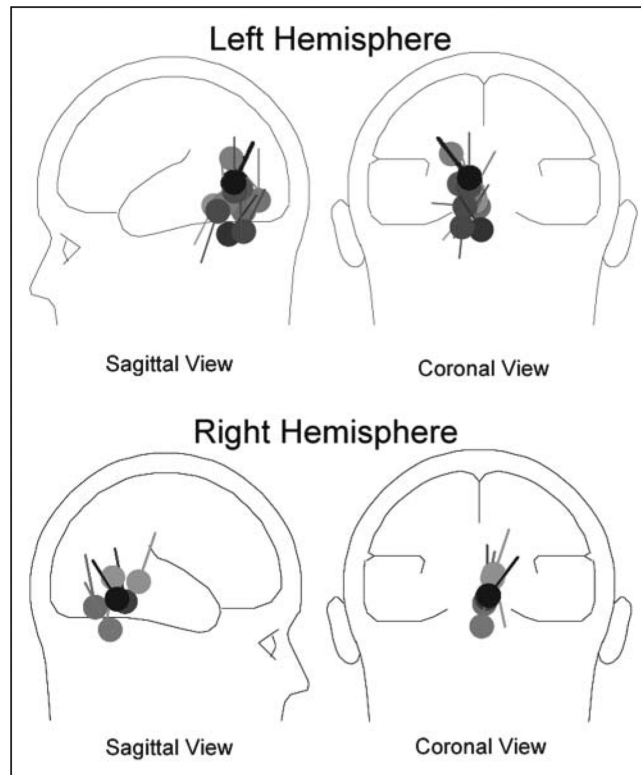


Figure 5. ECD source locations and dipole orientations for the component peaking at approximately 220 msec across all experimental conditions. The location of the dipoles resembles that typical of the M170 (e.g., Harris et al., 2008; Pylkkänen et al., 2006). Moreover, although there is greater variability in the orientations of the dipoles in our source models, the spatial locations across participants appear to be more consistent here than reported by Harris et al. (2008). The black dipole represents the grand average location and orientation calculated over participants for each hemisphere, whereas the gray dipole markers represent fits for individual participants.

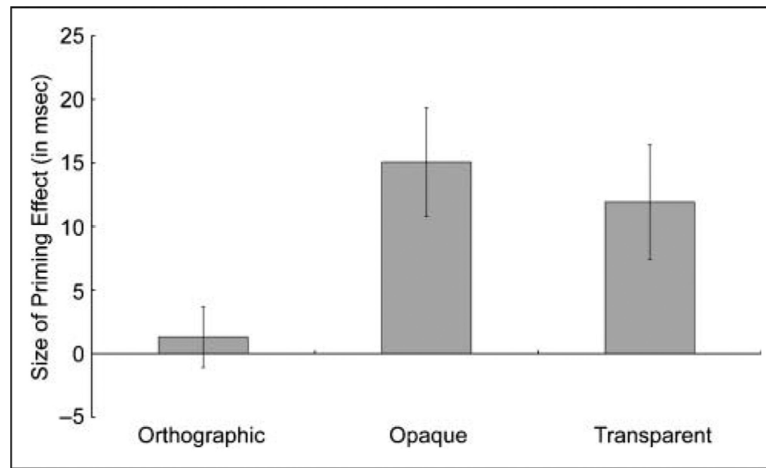


Figure 6. Magnitude of priming observed in the MEG latencies of the component peaking, on average, at 220 msec for the different conditions (unrelated vs. related).

Table 1

Mean RTs (msec), Error Rates (%), and Priming Effects (Unrelated Minus Related) for the Different Conditions

<i>Relatedness</i>	<i>Condition</i>					
	<i>Transparent</i>		<i>Opaque</i>		<i>Orthographic</i>	
	<i>RT</i>	<i>% Error</i>	<i>RT</i>	<i>% Error</i>	<i>RT</i>	<i>% Error</i>
Related	607 (64)	3.5 (2.6)	634 (64)	6.1 (5.0)	653 (65)	9.0 (7.0)
Unrelated	639 (64)	5.3 (4.3)	654 (64)	6.4 (5.1)	663 (58)	10.1 (4.9)
Priming effect	32 (19)	1.8 (3.8)	20 (23)	0.3 (5.3)	10 (17)	1.1 (3.7)

SDs of the mean are in parentheses.

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Table 2

Mean RTs (msec), Error Rates (%), and Priming Effects (Unrelated Minus Related) for the TP Conditions

<i>Relatedness</i>	<i>Condition</i>							
	<i>Transparent</i>				<i>Opaque</i>			
	<i>High TP</i>		<i>Low TP</i>		<i>High TP</i>		<i>Low TP</i>	
	<i>RT</i>	<i>% Error</i>	<i>RT</i>	<i>% Error</i>	<i>RT</i>	<i>% Error</i>	<i>RT</i>	<i>% Error</i>
Related	610 (65)	4.0 (3.6)	606 (61)	3.0 (3.1)	664 (72)	9.3 (7.4)	610 (69)	3.0 (3.7)
Unrelated	651 (73)	5.3 (6.1)	624 (58)	5.3 (4.1)	676 (76)	9.8 (8.4)	636 (54)	3.0 (3.1)
Priming effect	41 (23)	1.3 (6.8)	18 (26)	2.3 (4.1)	12 (47)	0.5 (9.2)	26 (41)	0.0 (3.9)

SDs of the mean are in parentheses.

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Table 3

Mean MEG Latencies (msec), Amplitudes (fT), and Priming Effects (Unrelated Minus Related) for the Different Conditions

<i>Relatedness</i>	<i>Condition</i>					
	<i>Transparent</i>		<i>Opaque</i>		<i>Orthographic</i>	
	<i>Latency</i>	<i>Amplitude</i>	<i>Latency</i>	<i>Amplitude</i>	<i>Latency</i>	<i>Amplitude</i>
Related	214 (24)	218 (102)	209 (25)	207 (114)	216 (24)	219 (108)
Unrelated	226 (24)	210 (114)	224 (28)	204 (109)	217 (28)	218 (121)
Priming effect	12 (18)	-8 (34)	15 (17)	-3 (31)	1 (10)	-1 (37)

SDs of the mean are in parentheses.

Table 4

Mean MEG Latencies (msec), Amplitudes (fT), and Priming Effects (Unrelated Minus Related) for the TP Conditions

<i>Relatedness</i>	<i>Condition</i>							
	<i>Transparent</i>				<i>Opaque</i>			
	<i>High TP</i>		<i>Low TP</i>		<i>High TP</i>		<i>Low TP</i>	
	<i>Lat</i>	<i>Ampl</i>	<i>Lat</i>	<i>Ampl</i>	<i>Lat</i>	<i>Ampl</i>	<i>Lat</i>	<i>Ampl</i>
Related	213 (23)	227 (101)	218 (33)	223 (103)	213 (25)	203 (118)	201 (32)	213 (111)
Unrelated	218 (30)	213 (125)	218 (31)	221 (107)	225 (29)	203 (102)	227 (35)	226 (114)
Priming effect	5 (35)	-14 (47)	0 (24)	-2 (41)	12 (35)	0 (37)	26 (31)	13 (45)

SDs of the mean are in parentheses. Lat = Latencies; Ampl = Amplitudes.