OBSERVATION

Tracking Hierarchical Processing in Morphological Decomposition With Brain Potentials

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One important debate in psycholinguistics concerns the nature of morphological decomposition processes in visual word recognition (e.g., darkness = {dark} + {-ness}). One theory claims that these processes arise during orthographic analysis and prior to accessing meaning (Rastle & Davis, 2008), and another argues that these processes arise through greater temporal overlap between the activation of orthographic and semantic information (Feldman, O'Connor, & Moscoso del Prado Martín, 2009). This issue has been the subject of intense debate in studies using masked priming but has yet to be resolved unequivocally. The present study takes another approach to resolving this controversy by examining brain potentials as participants made lexical decisions to unprimed morphological (*darkness*), pseudomorphological (*corner*), and nonmorphological (*brothel*) stimuli. Results revealed a difference from ~190 ms between the nonmorphological condition and the other 2 conditions (which showed no differentiation), a likely correlate of morphological processing reliant exclusively on orthography. Only 60–70 ms later was there evidence of the activation of semantic information, when the pseudomorphological condition diverged from the other 2 conditions. These results provide unambiguous support for a hierarchical model of morphological processing whereby decomposition is based initially on orthographic analysis and is only later constrained by semantic information.

Keywords: visual word recognition, morphology, event-related potential

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It is widely acknowledged that words are analyzed in terms of their morphemic constituents during visual word recognition (e.g., "darkness" as {dark} + {-ness}). However, there is considerable disagreement around the nature of this decomposition process. One theoretical position states that morphologically complex words are subject to rapid morphemic segmentation based solely on orthographic information, and that this orthographically based decomposition is followed sequentially by the activation of the semantic properties of those morphemes (Rastle & Davis, 2008; also Rastle, Davis, & New, 2004). The other theoretical position states that

morphological decomposition arises by virtue of a much tighter coupling between orthographic and semantic processing. One such theory posits "near simultaneous access to the orthophonological and semantic properties of words" (Feldman, O'Connor, & Moscoso del Prado Martín, 2009, p. 684), and another suggests that recognition is based on two parallel pathways, one in which a coarse-grained orthographic code supports rapid access to semantic information, and another in which a fine-grained orthographic code is analyzed in terms of its morphemic constituents (Grainger & Ziegler, 2011; also Diependaele, Sandra, & Grainger, 2009). In contrast to the sequential account of Rastle and Davis (2008), both of these theories suggest that rapid access to semantic information in reading can constrain the initial decomposition of words into their morphemic constituents. This observation reports an electrophysiological study that adjudicates clearly between these theoretical positions.

The sequential account of Rastle and Davis (2008) has been supported by data demonstrating that the recognition of a stem target is facilitated by the prior masked presentation of any prime that appears to be morphologically related. Masked priming effects are observed both when there is a semantically transparent morphological relation (e.g., darkness-DARK) and when there is a pseudomorphological relation (e.g., corner-CORN), and the magnitude of these effects is greater than that observed when there is a simple nonmorphological form relation (e.g., brothel-BROTH; see Rastle & Davis, 2008, for a review). Electrophysiological studies have provided converging evidence of greater or earlier masked priming effects when there is a morphological or pseudo-

morphological relationship than when there is a form relationship at ~350–500 ms posttarget onset (i.e., the N400 component; Lavric, Clapp, & Rastle, 2007) and even earlier along the processing chain (circa 200–250 ms; Lehtonen, Monahan, & Poeppel, 2011; Morris, Grainger, & Holcomb, 2008).

However, researchers using meta-analytic techniques have observed that when all the data are examined, there is a small but significant priming advantage for semantically related morphological pairs (Feldman et al., 2009; also Davis & Rastle, 2010), lending support to the theories in which there is greater temporal overlap in the processing of orthographic and semantic information in reading (Diependaele et al., 2009; Feldman et al., 2009). Support for these temporal overlap accounts has also come from another brain-potential study (Morris, Frank, Grainger, & Holcomb, 2007), which reported a graded increase in the magnitude of masked event-related potential (ERP) priming from form to pseudomorphological to morphological conditions.

Because reaction time (RT) reflects the endpoint of the recognition process, it is difficult to determine whether these small semantic effects arise because (a) there is temporal overlap in the processing of orthographic and semantic information in individual subjects (as predicted by the temporal overlap accounts) or (b) the processing of semantic information always follows the processing of orthographic information (as predicted by the sequential account) but the effectiveness of the masking varies over subjects and items, thus yielding a small effect of semantic transparency on morphological decomposition when all of the data are pooled. This latter account is consistent with the well-documented interaction between prime exposure duration and semantic transparency on morphological priming, whereby effects of semantic transparency increase as prime exposure duration increases into the range of partial and full visibility (Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Although electrophysiological techniques have the temporal resolution needed to capture processes leading up to the behavioral response, their combination with masked priming may not be optimal for examining the relative timing of orthographic and semantic processes because the latter are severely limited by masking. To address this conundrum, Lavric, Rastle, and Clapp (2011) recently reported an ERP study in which they enabled the semantic processing of the prime by substantially increasing the prime–target interval, thus making the prime visible. Behaviorally, this manipulation is known to enhance priming in the morphological condition and reduce (or even reverse) priming in the pseudomorphological condition (Rastle et al., 2000). Yet, the ERPs revealed a nonmonotonic (biphasic) pattern of priming in the pseudomorphological condition: Initially, it was equivalent to priming in the morphological condition (and both conditions showed greater priming than the nonmorphological condition), whereas later pseudomorphological priming diminished to the level seen in the nonmorphological condition (Lavric et al., 2011).

Although the Lavric et al. (2011) results argue in favor of Rastle and Davis' (2008) sequential account of morphological processing, their ERP response to the target was still an indirect measure of the morphological and semantic processing of the prime. Here, we examine unprimed recognition of morphologically complex (e.g., darkness), pseudomorphological (e.g., corner), and nonmorphological (e.g., brothel) words to obtain a direct, online, electrophysiological measure of morphological decomposition. If decomposition is indeed orthography-based and precedes semantic access, we should observe an early effect of morphological structure: The morphological and pseudomorphological conditions should pattern together and differ from the nonmorphological condition. Furthermore, because the decomposition is inappropriate in the pseudomorphological condition (corner ≠ {corn} + {er}), "corrective" effects of semantic transparency (morphological vs. pseudomorphological) are likely to follow (cf. Lavric et al., 2011). Alternatively, if morphological decomposition arises through a tighter coupling between orthographic and semantic processing, then we would expect semantically transparent morphological items to have a different electrophysiological signature from the other two conditions and little differentiation between the latter.

A similar approach was adopted in a recent magnetoencephalography (MEG) study (Zweig & Pylkkänen, 2009), which did reveal early (~150–200 ms) differentiation between conditions equivalent to our morphological and nonmorphological form conditions. Unfortunately, the results for the pseudomorphological words were equivocal: In some analyses, they seemed to pattern with the morphological items, whereas in other analyses of the same MEG component (M170) they diverged significantly from the morphological items. We aimed to clarify the time course of processing of pseudomorphological items.

Method

Participants

Twenty-eight right-handed native English speakers (11 women; mean age = 25.8 years, SD = 5.9) received course credits or £7 for their participation.

Apparatus

The experiment was run using E-Prime 1.1 (Sharpsburg, PA), and a standard PC, keyboard, and 17-in. CRT monitor. The electroencephalogram (EEG) was acquired using a 64-Ag/AgCl-electrode cap and BrainAmp amplifiers (BrainProducts, Munich, Germany).

Stimuli

The critical stimuli were three sets of 63 English words (see Supplementary Material), closely matched (see Table 1; Fs < 1) on orthographic and phonological length, orthographic neighborhood density, and CELEX frequency (Baayen, Piepenbrock, & van Rihn, 1993). The first (morphological) set comprised morphologically complex words consisting of a stem and a derivational suffix, for example, teacher. The second (pseudomorphological) set comprised morphologically simple words that could be perfectly segmented into a real stem and an ending identical to a real suffix typically also occurring in the morphological condition, for example, corner. The third (nonmorphological) set comprised morphologically simple words that contained an embedded word

Table 1
Means (Standard Deviations) of Items

Condition	*n*	Orthographic length	Phonological length	Neighborhood density (*N*)	Frequency/million
Morphological	63	7.37 (1.05)	6.78 (1.49)	1.06 (3.08)	20.05 (58.75)
Pseudomorphological	63	7.46 (1.33)	6.79 (1.33)	1.37 (2.40)	23.73 (65.18)
Nonmorphological	61	7.23 (1.60)	6.70 (1.93)	1.02 (1.75)	18.75 (31.90)

but no real or apparent suffix, for example, *freeze.*[1] Finally, 189 pronounceable nonwords were matched to the words on orthographic (*M* = 7.25) and phonological (*M* = 6.77) length. Two thirds of them contained an apparent English suffix, for example, *breen**er**.

Procedure

Participants classified each stimulus as an English word or not using right and left index finger key presses, with the right–left assignment counterbalanced across participants. Forty practice trials preceded the testing. Each trial started with a 1-s fixation cross followed by the letter string (in bold upper case Courier New font, size 18) until a response was made. Errors were followed by the feedback "INCORRECT" for 2 s; otherwise, a blank screen followed the response for 2 s.

EEG/ERPs

The EEG was acquired from 64 (58 scalp) electrodes (sampling rate, 500 Hz; bandpass, 0.016–100 Hz; reference, Cz; ground, AFz; impedance < 10 kΩ), and subsequently low-pass filtered (30 Hz, 24 dB/octave), rereferenced to the average of the earlobes, and segmented into 550-ms epochs time-locked to stimulus onset plus a 100-ms prestimulus baseline. Segments were baseline-corrected, and those containing ocular, muscle, and other artifacts were removed following visual inspection.

To examine early processes in visual word recognition, we subjected the initial 300 ms of the ERP to the following analysis: (a) Global field power (a measure of activity over all electrodes) was calculated collapsing over condition to identify periods of peak activity; (b) voltages were averaged in time windows set around those peaks; then (c) averaged for 10 scalp regions (see Figure 1); and (d) submitted to analyses of variance (ANOVAs). Significance levels were Huynh–Feldt-corrected for sphericity violations, but unadjusted degrees of freedom are reported.

Results

Behavioral Results

Five words with more than 40% errors were removed from the analysis (*acreage, nymphet, tufted, basilica, jerkin*). The ANOVAs on the RTs and error rates yielded a significant main effect of condition by participants, $F_{RT}(2, 54) = 10.41$, $p < .001$; $F_{Err}(2, 54) = 7.98$, $p = .001$; and by items, $F_{RT}(2, 178) = 3.68$, $p = .027$; $F_{Err}(2, 178) = 2.48$, $p = .087$. Follow-up *t* tests (see Table 2) revealed significantly longer RTs and more errors in the nonmor-

phological condition than the other conditions, which did not differ reliably.

ERPs (see Figure 1)

Four 30-ms time windows set around the global field power maxima within the first 300 ms (86–116 ms, 136–166 ms, 190–220 ms, 246–276 ms) were each subjected to a Condition (3) × Region (5) × Hemisphere (2) ANOVA, and, if required, to follow-up ANOVAs on pairs of conditions.

The analysis of the two earliest time windows revealed no statistically significant effects involving condition. In the 190–220-ms time window, the main effect of condition was significant, $F(2, 54) = 6.34$, $p = .005$, reflecting greater negative-polarity voltages in many central and posterior electrodes for the nonmorphological condition than in the morphological, $F(1, 27) = 10.87$, $p = .003$, and pseudomorphological, $F(1, 27) = 12.60$, $p = .001$, conditions; the latter two patterned together (no detectable difference, $F < 1$).

There was also a main effect of condition, $F(2, 54) = 5.58$, $p = .006$, in the 246–276-ms time window, which comprised a positive-polarity peak maximal in central and parietal electrodes (see Figure 1). Here, the pattern of contrasts was different from the previous time window: The pseudomorphological condition differed from both the morphological condition, $F(1, 27) = 11.34$, $p = .002$, and nonmorphological condition, $F(1, 27) = 4.54$, $p = .042$, whereas the latter two did not differ ($Fs < 1.2$). No interactions between condition and region and/or hemisphere approached significance for this or the preceding time window.

An ANOVA with the additional factor time window assessed the transition from one pattern of differences at 190–220 ms to the other at 246–276 ms. The critical interaction between condition and time window was significant, $F(2, 54) = 3.07$, $p = .05$.

The sequential account of morphological decomposition predicts two effects: (1) a difference between pseudomorphological and nonmorphological conditions at the time of the earliest difference between the morphological and nonmorphological conditions, and (2) no difference between pseudomorphological and morphological conditions at this early latency. Although our analysis of the 190–220-ms time window clearly supports the first effect, it is mute about the second because conventional inferential statistics cannot assess the evidence in favor of the null hypothesis. We therefore used Bayesian statistics to estimate the likelihood of

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[1] Following testing it was discovered that two morphologically complex items were assigned to the nonmorphological set: *tactile* and *textile*. They were discarded from all behavioral and ERP analyses; the statistics on psycholinguistic variables (length, frequency, N) also exclude these items.
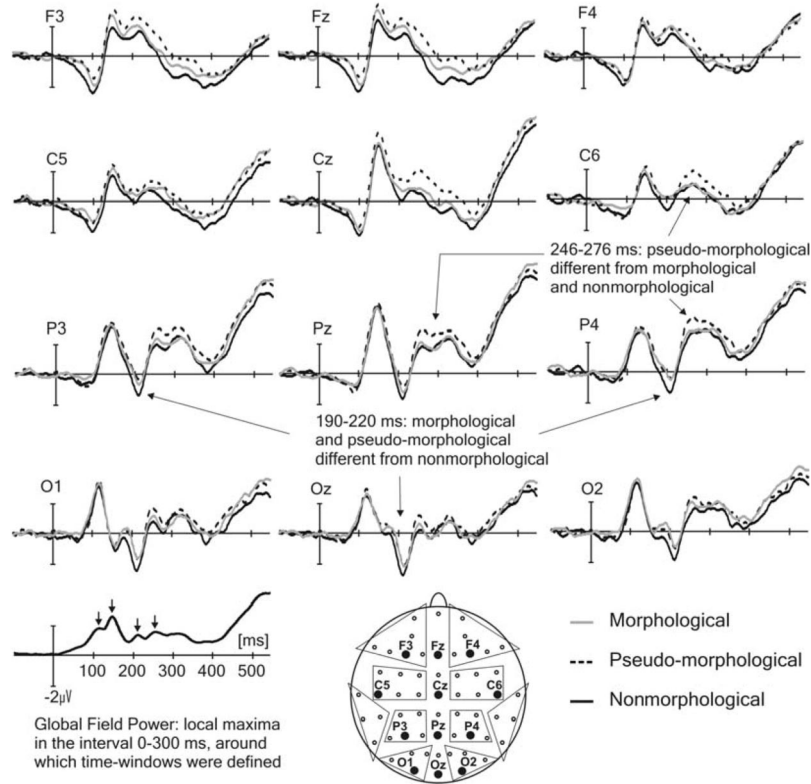
Figure 1. Event-related potentials (ERPs) for the three conditions in several representative electrodes and the global field power plot. The schematic head surface shows the electrode positions (emphasizing the electrodes in the ERP plots) and the scalp regions for which voltages were averaged prior to analyses of variance. There five regions on the left (anterior frontal [FP1, AF3, F1, F3, F5, F7], posterior frontal [FC1, FC3, FC5, C1, C3, C5], temporal [T7, TP7, CP5, P7], parietal [CP1, CP3, P1, P3, P5], parietal–occipital [PO1, PO3, PO7, O1]) and the corresponding regions on the right; midline electrodes were not analyzed (see Weber & Lavric, 2008, for details on the benefits of this grouping of electrodes).

the null hypothesis being true by computing the posterior probability of the null hypothesis given the new data.

Using the method recently proposed by Masson (2011), we computed the Bayes factor and the posterior probabilities for H_0 and H_1 using the sums of squares for the main effect of condition (effect, 1.42; error, 275.27) from the ANOVA on the pseudomor-

phological and morphological ERPs. The resulting posterior probabilities were .83 for H_0 and 0.17 for H_1. According to Raftery's (1995) classification of evidence based on probability values into "weak" (.5–.75), "positive" (.75–.95), "strong" (.95–.99) and "very strong" (>.99), the ERP amplitudes in the 190–220-ms time window provide positive evidence for H_0 (no difference between

Table 2
Mean (Standard Deviation) Reaction Times (RTs), Error Rates, and Pairwise t-Test Results (by Participants and Items)

Condition	RT (ms)	Error rate (%)
Morphological	716 (117)	3.7 (3.8)
Pseudomorphological	722 (122)	4.6 (4.2)
Nonmorphological	748 (125)	6.6 (5.1)
Morphological vs. nonmorphological	$t_p(27) = -4.2, p < .001^*$	$t_p(27) = -3.95, p = .001^*$
	$t_i(116) = -2.47, p = .015^*$	$t_i(116) = -2.04, p = .043$
Pseudomorphological vs. nonmorphological	$t_p(27) = -3.29, p = .003^*$	$t_p(27) = -2.38, p = .025^*$
	$t_i(120) = -2.01, p = .047$	$t_i(120) = -1.5, p = .136$
Morphological vs. pseudomorphological	$t_p(27) = -0.86, p = .4$	$t_p(27) = -1.38, p = .178$
	$t_i(120) = -0.57, p = .567$	$t_i(120) = -0.69, p = .489$

Note. Asterisks indicate statistically significant differences corrected for multiple comparisons using the Holm–Bonferroni procedure.

the pseudomorphological and morphological conditions as predicted by the sequential account) and less than weak evidence for H_1 (the two conditions are associated with different patterns of electrophysiological signals as predicted by the temporal overlap account). In computing these posterior probabilities, we assumed "noninformative priors" (no preexisting preference for either hypothesis). If one does assume some bias toward H_0 based on previous data (e.g., that it is twice as likely as H_1), the posterior probabilities become .91 for H_0 and .09 for H_1. Finally, we used the same procedure to evaluate the difference between the pseudomorphological and nonmorphological conditions at 190–220 ms. The posterior probabilities of .02 for H_0 and .98 for H_1 indicated that the evidence for H_1 (the two conditions are associated with different patterns of electrophysiological signals as predicted by the sequential account) is strong, whereas the evidence for H_0 is less than weak. As above, these computations were based on noninformative priors; the evidence is even more categorical if one assumes priors favoring H_1.

Discussion

Masked priming data have not been entirely unequivocal vis-à-vis morphological decomposition, because small yet significant differences between morphological (e.g., hunter-HUNT) and pseudomorphological (e.g., corner-CORN) priming may reflect variability in the effectiveness of masking over participants (Rastle & Davis, 2008) or suggest that morphological processing is subject to semantic influences from its earliest stages (Diependaele et al., 2009; Feldman et al., 2009).

Using online electrophysiological monitoring of unprimed visual word recognition, we reasoned that a purely orthographic morphological segmentation mechanism should not differentiate between morphological (dark*ness*) and pseudomorphological (cor*ner*) stimuli, but it should differentiate between both of these word types and words in which there is not even an appearance of morphological complexity (brothel); only later should semantics "override" the inappropriate decomposition of pseudomorphological stimuli. Conversely, if morphological decomposition is influenced by semantic information from its earliest stages, the clearest and earliest effect one would expect to see is a difference between the morphological condition and the other two conditions.

Of the two hypothesized patterns, our results are clearly consistent with the former. At ~190–220 ms following word onset, the nonmorphological condition had different ERP amplitudes from the morphological and pseudomorphological conditions, whereas there were no discernable differences between the latter two conditions (see Figure 1). The potentials in the pseudomorphological condition differed from those in the other two conditions 60–70 ms later, consistent with the sequential activation of semantic information. We believe the latter positive-polarity deflection for the pseudomorphological condition relative to the morphological condition (see Figure 1) may reflect some type of rectification of the inappropriate segmentation of pseudomorphological items that becomes apparent only once semantic information has been activated.

To our knowledge, this is the first evidence for the sequential account of morphological decomposition in a paradigm that contrasted the (unprimed) recognition of morphologically complex, pseudomorphological, and nonmorphological words. Our data are

consistent with recent correlational MEG studies (e.g., Lewis, Solomyak, & Marantz, 2011; Solomyak & Marantz, 2010) showing earlier effects of morphological (e.g., affix frequency) than lexicosemantic (lemma frequency) properties in word recognition. Furthermore, our early effect of morphological structure on the ERPs at ~190 ms has a very similar timing to the M170 morphological effects reported in these studies.

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