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A visual M170 effect of morphological complexity

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Abstract

Recent masked priming studies on visual word recognition have suggested that morphological decomposition is performed prelexically, purely on the basis of the orthographic properties of the word form. Given this, one might expect morphological complexity to modulate early visual evoked activity in electromagnetic measures. We investigated the neural bases of morphological decomposition with magnetoencephalography (MEG). In two experiments, we manipulated morphological complexity in single word lexical decision without priming, once using suffixed words and once using prefixed words. We found that morphologically complex forms display larger amplitudes in the M170, the same component that has been implicated for letterstring and face effects in previous MEG studies. Although letterstring effects have been reported to be left-lateral, we found a right-lateral effect of morphological complexity, suggesting that both hemispheres may be involved in early analysis of word forms.

Exactly how linguistic input is decomposed into its basic computational units is one of the core questions for theories of language processing. This problem is obviously the most challenging for the auditory modality, where even major structural boundaries may lack any reliable marking. In reading, however, detecting word and sentence boundaries is usually trivial and, thus, the main challenge has been to understand whether and how complex words are further broken down into their constituent morphemes. We investigated this question with magnetoencephalography (MEG), with the aim of identifying what neural activity, if any, is sensitive to morphological complexity in the visual modality.

An interesting generalization has emerged from recent behavioral studies on decomposition in reading. According to this research, the processor not only decomposes morphologically complex words such as *teacher*, but also words such as *corner*, which is not a derivative of *corn* in any theory, but nevertheless superficially contains an existing stem, *corn*, and an existing affix, *-er*. The evidence comes from masked priming, where the primes are presented so briefly that they are not consciously perceived. Longtin, Segui, & Hallé (2003) reported equivalent priming in French for semantically transparent (*gaufrette-GAUFRE* ''wafer-waffle''), semantically opaque (*fauvette-FAUVE* ''warbler-wildcat'') and pseudo-derived (*baguette-BAGUE* ''little stick-ring'') primes and no priming for orthographically related prime-target pairs such as *abricot-ABRI* (''apricot-shelter''). The pseudo-derived primes were superficially decomposable into the target stem and an affix, but crucially there was no semantic or etymological relationship between the prime and the target. This was in contrast to the orthographically related condition, where the prime contained the target but the remaining material (*-cot*) did not form an existing suffix. Similar results were found for English by Rastle, Davis, & New (2004), who obtained equivalent masked priming for semantically transparent

(*cleaner-clear*) and pseudo-derived primes (*brother-broth*) and no priming for primes that were only orthographically related to their targets (*brother-broth*).

These results suggest that visual word recognition involves a presemantic processing stage where anything that looks complex is decomposed on the basis of orthographic properties alone (Longtin et al., 2003; Rastle et al., 2004). This type of view was originally proposed by Taft and Forster (1975), who also argued that decomposition is obligatory and prelexical. In those cases where presemantic decomposition leads to an incorrect analysis, as for the pseudoderived *brother*, we would expect priming between the "derived" form and the pseudostem (*broth*) to be rather short lasting. Indeed, in paradigms where the prime is consciously perceived, semantic transparency is generally required for reliable priming between related forms (Feldman & Soltano, 1999; Marslen-Wilson et al., 1994; Rastle et al., 2000). For example, Longtin et al. (2003) showed that the same opaque and pseudoderived stimuli that showed positive priming in masked priming failed to elicit any priming in crossmodal auditory-visual presentation, where only the semantically transparent primes facilitated target processing.

Thus it appears that splitting words into morphemes is the default mode of the language processor. Consequently, characterizing the neural bases of morphological decomposition is a central goal for the cognitive neuroscience of language. Given the behavioral masked priming literature, one would expect neural effects of form-based decomposition to occur in an early time window, potentially in visual areas. In order to identify decomposition related activity, we conducted two MEG experiments where complex and simple forms where contrasted in single word lexical decision.

Surprisingly, there are relatively few existing neurolinguistic studies aimed at identifying decomposition related activity. Several ERP studies have compared correct and incorrect forms

of verbal inflection in various languages, finding that the type of violation response depends on whether the morphology is regular or irregular (Penke, Weyerts, Gross, Zander, Münte, & Clahsen, 1997; Rodriguez-Fornells, Clahsen, Lleó, Zaake & Münte, 2001; Weyerts, Penke, Dohrn, Clahsen & Münte, 1997). However, recognizing that an affix is ungrammatical may plausibly depend on successful decomposition. Consequently, violation studies do not necessarily detect neural correlates of decomposition. Whether decomposition effects occur early or late was, however, directly investigated in ERPs by Lehtonen, Cunillera, Rodríguez-Fornells, Hultén, Tuomainen & Laine (2007), who contrasted inflected and monomorphemic Finnish words and found an effect of complexity only in the N400 time-window. Thus, to our awareness, there are no extant reports of complexity effects at 100-200ms, i.e., in the time-window of visual evoked components in EEG and MEG.

Functional neuroimaging studies, offering good spatial accuracy but little temporal resolution, have reported effects of complexity in various left hemisphere structures. In an fMRI study, Vannest, Polk and Lewis (2005) found that complex English words with derivational affixes show more activation than either monomorphemic or inflected words in both Broca's area and the basal ganglia. A PET study by Laine, Rinne, Krause, Teräs, & Sipilä (1999) and an fMRI study by Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine (2006) have also shown that inflected Finnish words elicit more activation in the left inferior frontal, left posterior middle and superior temporal gyri during word recognition and encoding in memory. In addition to these effects, Lehtonen et al. (2006) did also find a somewhat less reliable effect in the left fusiform gyrus, i.e., in the so-called "visual word form area." This may constitute some tentative evidence for the participation of higher level vision in morphological decomposition. Overall though,

hemodynamic methods have not yielded any clear-cut evidence in favor of decomposition effects in visual areas.

We investigated whether early effects of decomposition might be revealed by MEG, which combines millisecond temporal resolution with relatively good spatial accuracy. Many studies have investigated the MEG responses elicited by visual words. The first two components, the visual M100 and the visual M170 are not specific to words but are rather elicited by any complex image. The visual M100 is generated in posterior midline regions in the vicinity of V1 cortex and peaks around 100-130ms (Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003; Tarkiainen, Cornelissen, & Salmelin, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). This response is modulated by noise and the size of the stimulus, but shows no sensitivity to the contrast between letter strings and other visually similar stimuli. Consequently, the visual M100 (or "Type I activity") has been hypothesized to reflect low-level visual feature analysis (Cornelissen et al., 2003; Tarkiainen et al., 2002). In EEG, orthographic typicality has been found to modulate activity at ~100ms (Hauk, Davis, et al., 2006; Hauk, Patterson, et al., 2006), but whether this effect is generated by the same sources as the letter string effects of Cornelissen et al., (2003) and Tarkiainen et al. (2002) is unclear. Outside of language, one study has reported content-sensitivity in the visual M100 in the form of increased amplitudes for faces as opposed to houses (Liu, Harris, & Kanwisher, 2002). Thus there may be an asymmetry between linguistic and face stimuli in the depth of the analysis performed by the M100 generator.

The M170 (or "Type II activity" in Tarkiainen et al., 1999) has bilateral generators in inferior posterior occipitotemporal regions, peaking at 150-200ms. The left hemisphere generator shows greater activity for letter-strings than for symbol strings (Tarkiainen et al., 1999, 2002) and the right hemisphere generator increased amplitudes for face stimuli (Liu et al., 2002; Lueschow et

al., 2004; Tarkiainen et al., 2002). However, bilateral face effects have also been reported (e.g., Liu, Higuchi, Marantz, & Kanwisher, 1999). Overall, the M170 seems to perform object-level processing, with potential lateralization differences between categories (Tarkiainen et al., 2002).

The MEG M170 literature converges well with the corresponding hemodynamic studies, where letter-string effects have consistently localized to left inferior posterior temporal regions, or more specifically to the left fusiform gyrus (Cohen et al., 2000; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002) and face effects to the right fusiform gyrus (Kanwisher, McDermott & Chun, 1997; Tong, Nakayama, Moscovitch, Weinrib & Kanwisher, 2000). Consequently, these areas have been dubbed the Visual Word Form Area (VWFA) and the Fusiform Face Area (FFA), respectively.

Since the left hemiphere M170 generator is the first MEG response to show special sensitivity to letter strings as opposed to other visually similar stimuli, it is an obvious candidate for an early neural index of morphological decomposition. If decomposition effects are observed at the M170, this would suggest that the M170 generator is capable of extracting forms of morphemes from within a complex word.

An M170 effect of morphological complexity would offer further support to prelexical decomposition, if it is indeed the case that the M170 reflects prelexical processing, as argued by many researchers (Cornelissen et al., 2003; Pylkkänen & Marantz, 2003; Salmelin, 2006; Salmelin & Kujala, 2006; Tarkiainen et al., 1999, 2002). A prelexical interpretation of the M170 is supported by a sizeable body of MEG studies that have manipulated factors affecting lexicosemantic access and found left-lateral effects at 300-400ms, at the so-called M350/N400m, but not at the M170 (Beretta, Fiorentino, & Poeppel, 2005; Embick et al., 2001; Fiorentino & Poeppel, in press; Pylkkänen et al., 2001, 2002, 2004, 2006; Sekiguchi, Koyama, & Kakigi,

2001, 2004; Stockall & Marantz, 2006). Similarly, a large number of ERP studies have reported effects of lexico-semantic factors at the N400, and not earlier (for a review, see for example Kutas & Federmeier, 2000). However, there have also been MEG studies showing effects of lexical frequency at the M170 stage, or perhaps even earlier. In two MEG studies, one using a single subject and the other a group, Assadollahi & Pulvermüller (2001, 2003) reported an effect of lexical frequency already at 120-170ms for short words and a somewhat later effect for long words. This was interpreted as showing that nonphysical properties of words are processed already at 120-170ms. This finding has been corroborated by EEG studies where frequency effects have also been reported in this very early time-window (Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Sereno et al., 1998; Sereno & Rayner, 2003).

However, the recent evidence for stored representations of non-semantic visual word forms, reviewed above, raises the possibility that the early frequency effects could reflect prelexical access to form representations, as opposed to more abstract morpheme representations. This is a distinction that will need to be addressed in future work. Notice that an account of early frequency effects in terms of access to stored visual representations also predicts that lexicality should affect processing in roughly the same time-window as frequency. This result was, in fact, obtained by Hauk et al. (2006). However, in a similar time-window Hauk et al. also found an effect of so-called "semantic coherence", a measure of the degree of semantic relatedness among the members of the morphological family of the stimulus word. Although this factor has not been extensively studied in the context of lexical access models, this finding is currently perhaps the best electrophysiological evidence for some type of a semantic effect before 200ms.

In sum, there is a controversy in the current MEG/EEG literature with respect to the timing of lexical access. Although elucidating this debate was not the goal of the current investigation, our study does indirectly address it, at least if interpreted in the context of the masked priming literature reviewed above. Namely, if decomposition is prelexical, as strongly suggested by the masked priming results (Longtin et al., 2003; Rastle et al., 2004), then the earliest neural correlate of morphological complexity would, consequently, reflect processing at a prelexical processing stage.

As stated above, the primary aim of this study was to identify the earliest neural correlate of morphological complexity, whatever that may be. Instead of measuring the consequences of prime decomposition on target processing, which has been the main method of the behavioral literature, we aimed to measure decomposition directly by contrasting simple and complex words in single word lexical decision. A neural effect of decomposition that is not dependant on priming would provide a valuable novel dependent measure for the study of morphological processing.

The studies of Longtin et al. (2003) and Rastle et al. (2004) have shown that decomposition requires the presence of an affix: *brother* decomposes but *brothel* does not, despite the presence of a "pseudo-stem" in *brothel*. To account for this, Longtin et al. propose that decomposition requires the simultaneous presence of both a stem and an affix. However, neither Longtin et al. nor Rastle et al. tested whether decomposition might be primarily driven by the presence of an affix, with the lexicality of the remaining material being irrelevant. In a priming paradigm this would be difficult to test as it would require using a nonword target, as in *winter-WINT*. Since we employed simple lexical decision, including a NonStem-Affix condition was possible. Under Longtin et al.'s hypothesis, one would expect these to show no decomposition effects. In

contrast, in Taft and Forster's Affix Stripping Model (Taft & Forster, 1975), affixes are stripped whether or not the remaining material constitutes an existing stem. This would predict *winter* to pattern with complex forms such as *teacher* at the initial stage of decomposition.

EXPERIMENT 1

Suffixed and monomorphemic words were contrasted in a simple lexical decision task. We used a single suffix, *-er*, because this best allowed us to control for confounding factors such as word length and category. A large amount of non *–er* fillers was used to prevent participants from habituating to the presence of *–er*.

Method

Participants

Sixteen right-handed native speakers of English were paid for their participation. The participants were graduate and undergraduate students at New York University (ages 20-32, 9 female).

Materials

The stimuli were all nouns, 5-7 letters long. The main manipulation comprised of 3 bins of 34 words, as follows: (i) bimorphemic words ending with the suffix *-er* (*farmer*); (ii) monomorphemic orthographic controls (*winter*); and (iii) simple monomorphemic words (*switch*). All of the orthographic controls in condition (ii) were such that stripping off the final *er*

did not result in a valid English stem. All conditions were matched for number of letters ($F(2,33)$=0.16, p=0.85), surface frequency ($F(2,33)$=0.42, p=0.66; Kucera & Francis, 1967), lemma frequency($F(2,33)$=0.02, p=0.98; Kucera & Francis, 1967), orthographic neighborhood frequency ($F(2,33)$=1.37, p=0.26; Balota et al., 2002) and neighborhood density ($F(2,33)$=0.64, p=0.53). The only factor that ended up being imperfectly controlled for was number of syllables ($F(2,33)$=8, $p < 0.001$): monomorphemic words contained reliably fewer syllables than bimorphemic words (LSD $p < 0.0005$) and orthographic controls (LSD $p < 0.005$). But, importantly, bimorphemic stimuli and orthographic controls did not differ from each other in syllable count. Thus, an effect of complexity where the orthographic controls pattern with the other monomorphemic controls would not be explainable in terms of syllable count.

In addition to these conditions, our design contained a fourth bin of 34 *er*-suffixed words where the stem was a real word which had an opaque semantic contribution to the meaning of the whole word (*sweater*). This condition was matched to the other three conditions in all stimulus factors listed above and was included in order to assess the role of semantic transparency in any potentially elicited effect of complexity. The hypothesis that all words that look complex decompose in early stages of processing (Longtin et al., 2003; Rastle et al., 2004; Taft & Forster, 1975) would predict opaque items to pattern with transparent bimorphemic items at the decomposition stage. Unfortunately, however, we obtained no uniform pattern of results for our opaque items, different analysis methods yielding different results for this one condition. Thus our findings with respect to the opaque items remain inconclusive. Due to this complication, we delay discussion of the opaque items until the results of the other conditions, which do show a clear pattern, are reported. The lexical properties of all the four conditions are summarized in Table 1 and the items themselves in Appendix 1.

Fillers included 239 real and 375 non-words. Of the real word fillers, 188 were monomorphemic words, and 51 suffixed. 102 of the non-words ended in the letters *-er*, 51 ended in letters that spell another suffix (*quapist*), and 222 did not contain suffix-like endings.

Procedure

During the experiment, the participants lay in a dimly lit magnetically shielded room and viewed the experimental stimuli via fiber-optic goggles (Avotec, FL). Words were presented in nonproportional Courier font (size 80), one at a time, following a fixation of 500ms in the middle of the screen. At each word's appearance, the participants were required to press a button indicating whether it was a real word or not. The words disappeared on button press, or after 4000ms had elapsed.

Neuromagnetic fields were recorded with a whole-head, 148-channel neuromagnetometer array (4-D Neuroimaging, Magnes WH 2500) at a sampling rate of 678 Hz in a band between 1 and 200 Hz.

MEG Data Analysis

Data Preprocessing. Prior to MEG data analysis, erroneous trials and trials wherein the response time differed by more than 3 standard deviations from the subject's mean were excluded. MEG data were then cleaned of artifacts by rejecting all trials in which the difference between the minimum and maximum amplitudes exceeded a threshold, which varied between 2500-3600 fT, depending on the subject's amplitude range. In addition, any trial in which two neighboring time samples differed by more than 800 fT was rejected. Data were averaged by condition using an epoch length of 500 ms, preceded by a pre-stimulus interval of 100 ms. On average 22% of each

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subject's data were excluded due to errors or artifacts (SD 4.3%). Prior to source modeling,

MEG averages were low-pass filtered at 40Hz.

Areal Mean Signals. We achieved an initial measure of brain activity by calculating areal mean

signals (Hari, Portin, Kettenmann, Jousmäki & Kobal, 1997; Helenius, Salmelin, Service,

Connolly, Leinonen & Lyytinen, 2002). For every millisecond, the squares of the signals from all

the channels in each hemisphere were first summed and then the square root of the sum was

calculated. These values were then averaged over 20ms time windows. The resulting value

represented the total amount of activity in each hemisphere in each 20ms time window.

Dipole Modeling. As a second analysis, a multiple-source model (Brain Electric Source

Analysis, 5.1), was applied to MEG activity elicited at 0-500ms. For each subject, data from all

real-word stimuli (including fillers, for a total of 375 words minus errors) were averaged together

for the purpose of source localization. This assured the best signal-to-noise ratio, and assured that

the same sources were compared for all conditions. All sensors were used in localization.

Sources were fit at the peaks of response components of interest, based on previous MEG

language studies in the visual modality (Embick et al., 2001, Helenius, Salmelin, Service, &

Connolly, 1998, Pylkkänen et al. 2004, 2006; Pylkkänen & Marantz, 2003; Pylkkänen,

Stringfellow, & Marantz, 2002; Tarkiainen et al., 1999). The methods used differed for different

components.

For the M170, there is strong fMRI evidence that the M170 field is generated in fusiform

gyri. Although the M170 field pattern is elicited by most complex visual stimuli, its left and right

generators show differential sensitivity to the content of the stimulus. The left hemisphere

generator shows a stronger response to letter strings (Tarkiainen et al., 1999) whereas the right hemisphere generator is sensitive to faces (Liu, Harris & Kanwisher, 2002; Tarkiainen, Cornelissen, & Salmelin, 2002). As reviewed above, in fMRI studies, letter-string effects have consistently localized to the left fusiform gyrus (Cohen et al., 2000; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002) and face effects to the right fusiform gyrus (Kanwisher, McDermott & Chun, 1997; Tong, Nakayama, Moscovitch, Weinrib & Kanwisher, 2000), suggesting that the M170 is generated in fusiform gyri bilaterally. However, despite the evidence that the M170 has bilateral generators in fusiform gyri, multidipole modeling of the M170 field pattern with BESA yielded mostly midline localizations of a single dipole, possibly because of the significant overlap between the magnetic fields associated with the left and right hemisphere sources of this activity. Since a single dipole midline solution was likely to be incorrect for the M170 (and this was confirmed by our distributed source modeling, see Results), M170 dipoles were seeded instead of fit to the data. Specifically, the left hemisphere generator of the M170 field was represented as a current source exactly in the mean location where Cohen et al. (2000) reported increased activation for letter strings (Talairach coordinates x=-42, y=-57, z=-6). The right hemisphere M170 source was made exactly symmetric to this (x=42, y=-57, z=-6). Thus M170 dipole location was kept constant across all subjects and conditions. M170 dipole orientation, on the other hand, was determined within subjects at the timepoint in which these dipoles accounted for the most activity ($M = 174$ms, SD 32ms). Dipole orientation was kept constant across conditions. Even though no other sources were included in the M170 models, the two fusiform dipoles accounted for a mean of 77.2% (SD 10.1%) of M170 activity across all sensors.

In addition to the two-dipole models of the M170 activity, source models were created both for visual M100 and M350 activity. As reviewed above, the visual M100 is sensitive to various physical stimulus factors such as noise and size, whereas the M350 is affected by a host of lexical-level factors. Since the generators of these two components are relatively straightforward to localize, traditional multidipole modeling was used. The visual M100 is associated with a left-lateral outgoing field and a right-lateral re-entering field over occipital sensors; such fields were found in all 16 subjects. The M350 features a posterior outgoing field and an anterior re-entering field over left temporal sensors; this type of field was found in 12 subjects. Multidipole models were created for the timepoints where the M100 and M350 field distributions were the clearest. Only dipoles that fell within the areas of activity in minimum norm estimates, and whose location and orientation were consistent with the magnetic field patterns, were accepted. At the end we had three multi-dipole models per subject, each accounting for activity at a single component (M100, M170 and M350). Each of these component-based models was then applied to each of the three conditions. The latency and amplitude values were measured at the peaks of the sourcewaves. If a source peaked multiple times in the time-window of interest, the peak at which the goodness-of-fit of the dipole was the highest was selected.

Distributed Source Analysis. As mentioned above, the generators of the M170 were difficult to model as discrete dipoles, possibly due to the overlapping magnetic fields associated with the bilateral sources of this activity. In order to assess the effect of our stimulus manipulation on M170 activity with a more objective method that the planted dipoles approach, we additionally carried out a distributed source analysis of the activity in the M170 time-window with Minimum Norm Estimates (MNEs). MNEs provide an estimation of current density across a large number

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of sources evenly distributed across the brain surface (Hämäläinen & Ilmoniemi 1984). MNEs have the advantage over dipole models of requiring no assumptions about the location or number of sources. Rather, the method implicitly incorporates side assumptions (here, e.g., a minimum L2-norm of the final current distribution is assumed). Further, unlike discrete source models, which are most accurate for focal sources, MNEs are also suitable for the representation of distributed sources (Hauk, 2004; Uutela, Hämäläinen, & Somersalo, 1999).

The minimum norm images were calculated in BESA 5.1. Each MNE was based on the activity of 1426 regional sources evenly distributed in two shells 10% and 30% below a smoothed standard brain surface. Regional sources in MEG can be regarded as sources with two single dipoles at the same location but with orthogonal orientations. The total activity of each regional source was computed as the root mean square of the source activities of its two components. The minimum norm images were depth weighted as well as spatio-temporally weighted, using a signal subspace correlation measure introduced by Mosher & Leahy (1998).

Pair-wise comparisons of the minimum total powers of the current distribution (the minimum L2 norm) associated with each experimental condition were carried out sample by sample. Two statistical tests were used. Each observation (i.e., a source amplitude at a time point) was included in two statistical tests: a point-by-point t-test, and a within-subjects non-parametric statistical permutation test based on 1000 random draws (Maris & Oostenveld, in press). We considered a point to show a reliable difference if both tests returned a p value of 0.05 or less for at least 25 milliseconds (17 samples) and if 10 of its closest neighbors were also at $p<0.05$ in both tests. Thus each significant effect represented the center of a spatio-temporal neighborhood showing a reliable difference between conditions.

Results

Behavioral data

Mean lexical decision times are shown in Table 2. No behavioral effects were found, suggesting that morphological complexity is not associated with a processing cost that is straightforwardly reflected in lexical decision times.

Areal Mean Signals

Figure 1 shows the areal mean signals for both hemispheres. An effect of condition was found in the right hemisphere (RH) at 150-170ms ($F(2,15)=3.9$, $p<0.05$). Pairwise comparisons showed that bimorphemic stimuli elicited larger amplitudes ($M = 88.6$ fT) than either monomorphemic ($M = 75.3$ fT, LSD $p<0.05$) or monomorphemic orthographically matched controls ($M = 74.3$ fT, LSD $p<0.05$). In the left hemisphere the conditions did not differ reliably. Thus the areal mean signals showed an effect of morphological complexity in the M170 time window, although the right-laterality of the effect was unexpected.

Dipole Models

In order to examine the effect of complexity in source space, we analyzed the timing course of activation of the visual M100, M170 and M350 dipoles. Consistent with the areal mean signals the visual M100 showed no effect of the stimulus manipulation.

As mentioned above, the M170 activity was modeled by bilateral sources placed in the fusiform gyri. M170 sourcewaves that peaked before 130ms (1 RH sourcewave) or after 230ms (4 LH and 4 RH sources) were excluded from calculations, as these fall outside the typical M170

time window. In the right hemisphere M170 generator, an effect of condition on amplitude was found ($F(2,15)=4.2$, $p<0.05$). Pairwise comparisons showed the bimorphemic words elicited more activation than orthographic controls (LSD $p<0.01$), displaying a clear effect of morphological complexity. The left hemisphere M170 also showed an effect of condition on amplitude ($F(2,15)=3.5$, $p<0.05$) although this was clearly not an effect of morphology as the bimorphemic and the non-orthographic monomorphemic words displayed similar peak amplitudes. No effect on latency was observed in either hemisphere. Figure 2 shows mean M170 sourcewaves for all conditions, and Table 3 summarizes peak values. No effects were found in the M350.

Overall, these results corroborate what was found in the areal mean signals. It appears that morphological complexity indeed modulates the M170. Further, the fact that the orthographic controls (*winter*) patterned with the other monomorphemic words supports the conception of Longtin et al. (2003) that decomposition depends on the presence of both an affix and a stem.

Distributed Source Analysis

Figure 3 plots all sources that met our significance criteria in the distributed source analysis. Given the results of the areal means and the dipole analysis, we compared the minimum norms in the time period commonly associated with the M170, i.e., at 140-200ms. Starting at 160ms, we found reliably larger source amplitudes for the bimorphemic condition in right posterior inferior regions when compared to either monomorphemic condition. No similar difference was found when comparing the two monomorphemic conditions to each other. Figure 4 plots the timecourse of activity in the right hemisphere posterior inferior region where the reliable amplitude increase

for bimorphemic words was observed. In addition, the timecourse of activity in the corresponding left hemisphere sources is plotted, showing a lack of any reliable effect.

In sum, we obtained a consistent right-lateral effect of complexity across three analysis methods: areal mean signals calculated in sensor-space, discrete dipole models as well as distributed source models. Further, the right posterior inferior localization of the complexity effect obtained with MNEs confirmed that the placement of the dipoles in the discrete source analysis was in the right region.

Opaque items

Although the three analysis methods discussed above yielded a consistent right-lateral effect of complexity for the transparent bimorphemic items, we did not obtained a similarly uniform pattern of results for the opaque *er*-suffixed words. Behaviorally, the opaque items did not differ reliably from any of the other conditions (all pairwise p's > 0.2). As regards the MEG data, recall that if the RH M170 effect obtained for the transparent bimorphemic items reflected prelexical orthographically based decomposition, a similar effect should also have been found for the opaque items. The results of the M170 dipole analysis indeed patterned consistent with this hypothesis. When the opaque items were included in the statistics, RH M170 peak amplitudes showed a reliable main effect of Condition ($F(3,15)=3$, $p<0.05$), peak amplitudes of the opaque items (M = 26.45) being larger than those of both the monomorphemic (M = 23.58) and the orthographic controls (M= 19.9) (Fig. 5A). In pair-wise comparisons these differences did not reach reliablity, but when the complex transparent and the opaque items were both treated as +morphologically complex in a one-way ANOVA, the effect of complexity on RH M170 amplitude was significant ($F(1,15)=5.89$, $p<0.05$).

Unfortunately, however, neither the areal mean signals nor the distributed source analysis replicated this finding. The peak amplitudes of the right hemisphere areal mean signals in the M170 time window were not different for the opaque items in comparisons to either the orthographic ($p = 0.6$) or the monomorphemic controls ($p = 0.15$) . In fact, the opaque items showed reliably smaller peaks than the transparent bimorphemic items (p < 0.05), even though in the M170 dipole analysis these conditions patterned together. The distributed source analysis also showed no right-lateral differences between the opaque items and the monomorphemic controls. The opaque and transparent complex items did, however, dissociate right-laterally, with right posterior regions showing reliably larger amplitudes for the transparent items starting at 140ms.

Thus although the dipole analysis suggests that our M170 effect extends to opaque affixed words, the areal means signals and the distributed source analysis point to the opposite conclusion. These results suggest a complicated processing profile for opaque derived words, which is perhaps not surprising given their ambiguous status as complex words. Most likely, the M170 decomposition effect extends to opaque words in some partial way underdetermined by our current analysis methods.

In Experiment 2, we sought to further elucidate the more straightforward effect obtained for the transparent items, by examining the effect of affix position on the laterality of the M170 amplitude increase.

EXPERIMENT 2

Given that the RH M170 has previously been associated with face and not letter-string effects (Liu et al., 2002; Tarkiainen et al., 2002), the right-laterality of our complexity effect was rather surprising. In Experiment 2, we tested an alternative explanation of the effect, in terms of lexicality as opposed to decomposition.

Our hypothesis was motivated by the fact that the visual field is split into two halves, the contents of the right visual field (RVF) being initially projected to the left hemisphere (LH), and the contents of the left visual field (LVF) to the right hemisphere (RH). The importance of taking this physical constraint into account in models of reading has been emphasized in the Split Processing Model of Shillcock and colleagues (McDonald & Shillcock, 2005; Shillcock, Ellison, & Monaghan, 2000; Shillcock & Monaghan, 2001). As described above, our stimuli were delivered to each eye separately via fiberoptic goggles. Since the words appeared at the center of each display, the suffix always appeared in the right visual field and most of the stem in the left visual field, assuming that subjects fixated approximately in the middle of the display. Thus the visual features of the majority of the stem were initially analyzed in the right visual cortex, raising the possibility that the right-lateral M170 effect could have been due to the RH detecting an existing word form (i.e., the stem) only in the case of the morphological complex forms. This hypothesis assumes that right-lateral occipitotemporal areas are capable of word form recognition, contrary to the standard model of reading, where information presented to the LVF/RH must be transferred to the left hemisphere VWFA for word form recognition (Cohen et al., 2000). Nevertheless, we conducted a second experiment aimed at addressing a lexicality driven account of our effect in Exp. 1.

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To test whether the right-laterality of the M170 effect in Exp. 1 was due to the positioning of the stem in the LVF, we employed prefixed words in Exp. 2, reversing the position of the stem and affix. We hypothesized that if the right-laterality of our M170 effect was solely due to stem positioning, the effect should be elicited in the left hemisphere for prefixed words. On the other hand, a right hemisphere effect for prefixed words would indicate that the right hemisphere plays a role in the processing of complex words that is independent of the stem's linear position.

Method

Participants

Ten right-handed native speakers of English were paid for their participation. Nine of the participants were undergraduate or graduate students at New York University, and one was a faculty member (ages 20-45, five females).

Materials

There are no noun-deriving prefixes in English that are productive to the same extent as *–er*. Therefore, the verbal prefix *re-* was used. The stimuli were all verbs, 5-8 letters long. They were divided into 3 bins of 32 words each, as follows: (i) bimorphemic words beginning with the prefix *re-* (*refill*); (ii) orthographic controls that started with *re-* (*reckon*); and (iii) monomorphemic words that did not start with *re-* (*rotate*). As in Exp 1, the orthographic controls were of the form AffixNonword. All conditions were matched for number of letters ($F(2,31)=0.03$, $p=0.96$), surface frequency ($F(2,31)=0.03$, $p=0.97$; Kucera & Francis, 1967), lemma frequency ($F(2,31)=0.41$, $p=0.66$; Kucera & Francis, 1967), number of syllables

($F_{(2,31)}=1.56$, $p=0.21$) and orthographic neighborhood density ($F_{(2,31)}=2.25$, $p=0.11$) and neighborhood frequency ($F_{(2,31)}=0.06$, $p=0.94$). Table 4 summarizes the lexical factors controlled for in the critical stimuli.

In addition to the critical stimuli, both real and non-word fillers were used. A total of 224 real word fillers, none of which started in *re-*, were divided into 176 monomorphemic words, and 48 prefixed words. A total of 320 non-words were divided into 96 non-words starting in the letters -*re*, 48 non-words starting in letters that spell out another prefix (*disgrake*), and 166 non-words that do not contain prefix-like beginnings.

Procedure and Data Analysis

The procedure and data analysis were identical to those in Exp. 1. On average 23% of each subject's data were excluded due to errors or artifacts (SD 8.3%). In determining the orientation of the M170 fusiform sources, dipole orientation was again determined at the timepoint in which these dipoles accounted for the most activity ($M = 177$ms, SD 25ms). As in experiment 1, the two fusiform dipoles accounted for a mean of 78% (SD 9.7%) of M170 activity across all sensors.

Results

Behavioral data

Lexical decision data are summarized in Table 5. As in Exp. 1, we obtained no reliable effect on the behavioral responses.

Areal Mean Signals

Areal mean signals are displayed in Fig. 6. Like in Exp. 1, morphologically complex words showed larger right hemisphere amplitudes at 150-170ms than either control condition. Unlike in Exp. 1, the left hemisphere data showed the same pattern. However, neither of these effects reached reliability. The M170 peak amplitudes and latencies are summarized in Table 6.

A significant effect of condition was found in the right hemisphere in the 190ms-210ms time window ($F(2,9)=4.4$, $p<0.05$), and another in the 310-330ms time window ($F(2,9)=4.3$, $p<0.05$), but neither of these effects were effects of morphological complexity.

Dipole Models

As in Exp. 1, M170 activity was modeled by placing bilateral sources in the fusiform gyri. One LH sourcewave that peaked after 230ms was excluded from calculations.

As shown in Fig. 7, the results of the source analysis paralleled those obtained from the areal mean signals in the same time window, except that the bilateral amplitude increase for morphologically complex words was now reliable (RH: $F(2,9)=3.5$, $p=0.05$; LH: $F(2,9)=4.7$, $p<0.05$). Pairwise comparisons showed that the bimorphemic condition differed reliably from the monomorphemic condition (LSD $p<0.05$) and orthographic controls (LSD $p<0.05$) in the left hemisphere. In the right hemisphere, they differed significantly from the monomorphemic condition (LSD $p<0.05$), and marginally from the orthographic control (LSD $p<0.1$). M170 latency and amplitude data are summarized in Table 6.

As in Exp. 1, no reliable effects of condition were found in either the M100 or the M350.

Distributed Source Analysis

Analysis of the distributed source activity associated with the three types of stimuli was conducted according to the same criteria as in Exp. 1. Fig. 8 plots all reliable effects of the stimulus manipulation. Consistent with the areal means and the source analysis, a reliable difference between the monomorphemic and bimorphemic conditions was found in left posterior inferior regions. However, unlike in the other measures, no effects were found in the right hemisphere. Further, the MNEs showed no reliable difference between the bimorphemic stimuli and the orthographic controls. Figure 9 plots the timecourse of the activity in the reliable LH sources as well as their right hemisphere homologues. In addition, a statistically reliable difference was found between the monomorphemic and bimorphemic conditions in a superior frontal region. The time course of this rather low amplitude superior activity is plotted in Figure 10.

Overall, the results of Exp. 2 were not as robust as those of Exp. 1, where areal means, dipole source waves and MNEs all produced reliable and consistent results. One reason for this may be the lower number of subjects in Exp. 2. The discrepancy between the M170 dipole results, showing a bilateral effect, and the MNE results, showing only a LH effect, may be due to larger between-subjects variance in the localization of the M170 in the right hemisphere. To see why this may be relevant, imagine a situation where a group of subjects all show an effect within a certain region, but there is no overlap in the actual surface areas exhibiting the effect across subjects. A dipole placed in the middle of this region might capture the effect in all the subjects, yielding a reliable effect, whereas a voxel-by-voxel, or, as in our case, a regional source by regional source, analysis would not. Thus the RH M170 sources generating the complexity effect in the dipole analysis of Exp. 2 may have been more widely distributed than in Exp. 2.

In summary, Exp. 2 was designed to test whether a right-lateral effect of complexity would be obtained also for prefixed words, which would suggest that the effect of Exp. 1 was due to complexity and not to recognition of the stem. A RH effect was indeed obtained reliably in the dipole analysis and as a trend in the areal mean signals. However, unlike in the results for suffixed words, all the analysis methods also suggested a left hemisphere effect of complexity for prefixed words. Our study underdetermines the interpretation of this bilateral effect, which needs to be addressed in future studies. At least three different explanations are possible. First, it is possible that the difference reflects a genuine difference in the neural bases of decomposing suffixed and prefixed words. Perhaps suffixed words are decomposed right-laterally and prefixed words bilaterally, for whatever reason. Second, the monolateral effect of Exp. 1 could have been due to a combined lexicality and complexity effect in the RH and the bilateral effect of Exp 2 to a left-lateral effect of lexicality and a right-lateral effect of complexity. Or, finally, it is possible that morphological decomposition is performed by the M170 generators, and there is no interesting generalization about laterality. Importantly, however, every account has to appeal to decomposition in some way, since that is the only stimulus factor that can explain the right-hemisphere effect obtained both in Exp. 1 and 2.

DISCUSSION

Our study aimed to examine what neural activity, if any, is sensitive to morphological complexity in the visual modality. In two experiments, we found an effect of complexity on the M170, a component that has previously been associated with letter string and face perception. This indicates that morphemes, in addition to letters and faces, are among the complex visual

objects that M170 activity is sensitive to. These results establish a starting point for using the M170 as a dependent measure in studies of morphological processing.

However, contrary to our expectations, the complexity effect was manifested in the right hemisphere, which is surprising in the context of previous research showing that letter string effects localize to the left hemisphere M170 generator. In order to test whether our right lateral effect could perhaps be explained as an early lexicality effect, generated by the right hemisphere "seeing" an existing stem in the left visual field only in the case of suffixed forms, we manipulated complexity with prefixed words instead. Although the prefix experiment yielded a more complicated set of results, a right-lateral effect of complexity was observed in the M170 dipole analysis, suggesting that the RH M170 generator is sensitive to complexity no matter what the linear ordering between the stem and the affix. But interestingly, prefixed words also elicited increased amplitudes in the left hemisphere M170 source, suggesting that factors other than complexity may also be at play. Thus, our dataset shows a general effect of complexity in the right hemisphere M170 and effect in the left hemisphere that may have a lexicality-based explanation.

Although the right M170 generator has not figured in previous studies of visual language processing, results similar to ours have been obtained in an fMRI study comparing the Japanese Kanji and Kana scripts (Nakamura, Dehaene, Jorbert, Le Bihan & Kouider, 2005). This study showed that Kanji, wherein words are composed of logographic symbols representing morphemes, elicits greater activity in the right fusiform gyrus, than Kana, which is syllabic. In light of our results, this main effect of script may, in fact, have been an effect of morphological complexity. Another similarity can be found with a hemifield study by Caplan, Holmes &

Marshall (1974), which showed that presentation to the right hemisphere improves recognition of complex –*er* words as compared to simple ones.

Our hypothesis that morphological complexity might affect early visual evoked activity stemmed from recent masked priming studies, which have suggested that morphological decomposition is performed prelexically, purely on the basis of superficial word form (Longtin et al., 2003; Rastle et al., 2004). In light of these masked priming results, one would predict the earliest neural activity sensitive to morphological complexity to reflect a prelexical processing stage. To the extent that our methods were sufficiently sensitive to observe the earliest such effect, our results support a prelexical interpretation of the M170 stage.

It is worth noting that the latency of the M170 is of course much longer than the stimulus-onset-asynchronies of the above-mentioned masked priming studies, where the targets were presented 50ms after prime onset. What the masked priming results tell us is that 50ms is long enough for the visual system to gather all the information that it needs for decomposition. According to our results, decomposition does not, however, occur until at about 170ms. The combination of our data and the evidence that a complex prime is decomposed even when the target follows it only after 50ms suggests that the decomposition of the prime can occur after the target is already visible. This is consistent with views of masked priming where the processing of the prime is not halted by the visual mask, but rather proceeds to higher levels of representation although subliminally (e.g., Badecker & Allen, 2002; Marcel, 1983).

Finally, our study addressed whether decomposition is performed whenever the visual system detects a possible affix (Taft & Forster; 1975) or whether the remaining material must also constitute a possible stem, as suggested by Longtin et al. (2003). With the exception of the minimum norm analyses of Exp. 2, all our measures support the latter hypothesis: forms

containing an affix and a nonword (*wint-er*, *re-ckon*) patterned with straightforwardly simple forms. This supports the notion that decomposition is sensitive to the lexicality of the stem. Consequently, the M170 generators must be able to detect not only the shapes of high frequency affixes but also the forms of open class items. In other words, our study has shown that, in addition to performing higher level vision more generally, the activity underlying the M170 is able to detect that *printer* has two parts whereas *winter* does not.

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Appendix 1: Critical stimuli of Experiment 1

Monomorphemic	Orthographic	Bimorphemic	Opaque
almond	anger	adviser	bouncer
balance	antler	baker	breather
barrow	banter	bidder	bumper
beard	barrier	boiler	buster
billiard	beaver	boxer	charter
broom	blunder	caller	computer
bubble	bluster	catcher	counter
button	cancer	charmer	drawer
cannon	canker	crafter	flyer
champ	cinder	dancer	folder
clown	clatter	digger	gutter
convent	cluster	diver	header
crutch	danger	driver	joiner
curtain	feather	dryer	locker
drizzle	fever	employer	merger
envelope	filter	faker	officer
fright	finger	farmer	patter
margin	fodder	freezer	plunger
marlin	garter	heater	poker
middle	gender	hunter	porter
notion	ginger	killer	poster
pheasant	grocer	loser	prayer
puddle	holster	observer	ranger
rocket	leather	offender	rubber
rumble	lumber	painter	scooter
scalp	monster	preacher	slipper
scout	otter	printer	sneaker
scramble	plaster	reviewer	steamer
socket	platter	rider	sweater
spark	roster	singer	teller
switch	silver	sinner	toner
tangle	tiger	sleeper	trailer
trickle	whimper	weaver	trucker
witness	whisper	winner	tumbler

Appendix 2: Critical stimuli of Experiment 2

Monomorphemic	Orthographic	Bimorphemic
abandon	rebuke	react
acquiesce	reckon	readjust
adapt	reconcile	reaffirm
applaud	recruit	reappear
assay	reflect	rearrange
bargain	refrain	rebound
barricade	refute	rebuild
beckon	regulate	recall
broil	reign	recapture
catalogue	reject	recite
compare	rejoice	recoil
creak	relieve	recount
croak	relish	recover
diagnose	remedy	redeem
donate	render	redirect
guarantee	repel	refill
knead	replenish	refinance
orate	reprieve	refine
plead	reproach	reform
rotate	repudiate	refuel
sacrifice	rescue	refund
salute	resemble	reissue
slaughter	resist	relive
sneak	resume	remind
sprinkle	retain	repay
squeak	retaliate	reproduce
straggle	retch	reread
suppress	retort	reside
surrender	retrieve	resign
sweep	revel	restore
volunteer	revert	restrain
wreak	revolve	rethink

Table 1

Summary of the lexical properties of the critical stimuli of Experiment 1.

	Monomorphemic	Monomorphemic Orth.	Bimorphemic	Bimorphemic Opaque
Length (letters)	6.21 (0.91)	6.26 (0.67)	6.32 (0.97)	6.41 (0.74)
Length (syllables)	1.74 (0.51)	2 (0)	2.05 (0.34)	1.97 (0.39)
Surface frequency	14.44 (25.4)	12.44 (16.05)	10.29 (11.61)	10.24 (18.43)
Lemma Frequency	16.88 (25.5)	16.68 (23.43)	15.94 (18.49)	15.08 (31.93)
Orthographic neighborhood density	4.18 (2.18)	4.62 (2.46)	4.82 (2.58)	4.82 (2.99)
Orthographic neighborhood frequency	6.52 (1.8)	6.14 (1.32)	6.72 (1.25)	6.33 (1.18)

Table 2

Lexical decision time results of Experiment 1. No behavioral effects were obtained.

	RT	Error rate
Monomorphemic	739.8	1.6%
Monomorphemic orth.	745.2	2.1%
Bimorphemic	731.1	1.7%

Table 3

Mean M170 peak amplitudes and latencies from Experiment 1.

	Left Hemisphere		Right Hemisphere	
	Peak Amplitude	Latency	Peak Amplitude	Latency
Monomorphemic	29.0 nAm	181 ms	23.5 nAm	186 ms
Monomorphemic orth.	25.6 nAm	170 ms	19.9 nAm	181 ms
Bimorphemic	28.1 nAm	175 ms	27.2 nAm	183 ms

Table 4

Summary of the lexical properties of the critical stimuli in Experiment 2.

	Monomorphemic	Monomorphemic Orth.	Bimorphemic
Length (letters)	6.56 (2.03)	6.75 (1.24)	6.84 (1.17)
Length (syllables)	1.97 (0.74)	2.22 (0.66)	2.19 (0.4)
Surface frequency	6.71 (7.75)	7.16 (6.27)	6.84 (8.82)
Lemma Frequency	19.56 (23.07)	19.63 (22.63)	15.34 (18.65)
Orthographic neighborhood density	1.28 (1.65)	1.43 (2.29)	0.59 (0.8)
Orthographic neighborhood frequency	6.81 (1.58)	6.5 (2.68)	6.62 (3.17)

Table 5

Lexical decision time results of Experiment 2. No behavioral effects were obtained.

	RT	Error rate
Monomorphemic non-orth.	744.8	11.9%
Monomorphemic orth.	785.6	10.4%
Bimorphemic	757.9	4.9%

Table 6

Mean M170 peak amplitudes and latencies from Experiment 2.

	Left Hemisphere		Right Hemisphere	
	Peak Amplitude	Latency	Peak Amplitude	Latency
Monomorphemic	26.8 nAm	175 ms	25.2 nAm	182 ms
Monomorphemic orth.	27.6 nAm	179 ms	26.3 nAm	174 ms
Bimorphemic	32.4 nAm	177 ms	30.7 nAm	175 ms

Figure Captions

Figure 1. Experiment 1 areal mean signals. Center diagram represents the sensor arrangement and the dividing line between left and right hemispheres. The areal mean signals of the right hemisphere sensors show reliably larger amplitudes for the bimorphemic items at around 170ms.

Figure 2. Experiment 1 mean M170 source waveforms, showing increased amplitudes for the bimorphemic items right laterally. Center diagram shows source dipole location plotted on a standard MRI. Individual subject waveforms were aligned at the peaks before averaging.

Figure 3. Experiment 1 minimum norm significant source clusters, representing the locations of all sources found to exhibit a reliable difference in amplitude over 20ms time periods, for each of the three pairwise comparisons between conditions.

Figure 4. Time course of minimum norm activity in Experiment 1. Right diagram plots mean activity in the right hemisphere sources that exhibit a reliable amplitude difference at ~170ms. Left diagram plots mean activity in the left hemisphere homologue of these sources. The contrast between the hemispheres reveals that the effect of complexity is clearly right-lateral.

Figure 5. Summary of RH M170 data including the opaque suffixed condition. Left diagram plots peak amplitudes of planted dipoles. Center diagram plots peak amplitude of areal means. Right diagram represents the locations of sources found to exhibit a reliable difference in amplitude between 160ms and 180ms for the three pairwise comparisons involving opaque suffixed stimuli..

Figure 6. Experiment 2 areal mean signals. Center diagram represents the sensor arrangement and the dividing line between left and right hemispheres. Bimorphemic items trend towards larger peak amplitudes in the M170 time window.

Figure 7. Experiment 2 mean M170 source waveforms, showing a reliable bilateral amplitude increase for the bimorphemic items. Center diagram shows source dipole location plotted on standard MRI. Individual subject waveforms were aligned at the peaks before averaging.

Figure 8. Experiment 2 minimum norm significant source clusters, reepresenting the locations of sources found to exhibit a reliable difference in amplitude over 20ms time periods, for each of the three pairwise comparisons between conditions.

Figure 9. Time course of minimum norm activity in Experiment 2 (inferior sources). Left diagram plots mean activity in inferior left hemisphere sources that exhibit a reliable amplitude difference. Right diagram plots the time course of activity in the right hemisphere homologue of this source cluster. In the left hemisphere, bimorphemic items elicit reliably larger amplitudes than the monomorphemic controls. No other differences are significant.

Figure 10. Time course of minimum norm activity in Experiment 2 (superior sources). Mean activity in the superior left hemisphere sources that exhibit a reliable amplitude difference is plotted.

Fig. 1

Fig, 2

Fig. 3

Fig. 4

Fig. 5

A. Peak amplitudes of RH M170 dipoles

B. Peak amplitudes of RH areal mean signals

C. Pair-wise Minimum Norm Estimates

Opaque vs. Monomorphemic

Opaque vs. Orthographic

Opaque vs. Transparent

Fig. 6

Fig. 7

Fig. 8

Fig. 9

L

R

Fig. 10