The neural basis of obligatory decomposition of suffixed words

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ABSTRACT
Recent neurolinguistic studies present somewhat conflicting evidence concerning the role of the inferior temporal cortex (IT) in visual word recognition within the first 200 ms after presentation. On the one hand, fMRI studies of the Visual Word Form Area (VWFA) suggest that the IT might recover representations of the orthographic form of words. On the other hand, influential MEG studies of responses from the occipito-temporal regions around 150 ms post-stimulus onset indicate recognition of letters as opposed to symbols but not a sensitivity to statistical properties of letter strings associated with word form representations. Recent MEG experiments support the position that the IT does represent the visual word forms of morphemes and performs morphological decomposition modulated by the statistical relations between morphemes by 170 ms post-presentation (at the M170 response). Responses to heteronyms show that the M170 does not make contact with the mental lexicon where word forms are connected to meanings. We report here an MEG study of pseudo-affixed words like brother, which masked priming studies have shown are decomposed in recognition. If the M170 response from IT does index obligatory morphological decomposition based on visual word forms but not lexical entries, we should find that the statistical relation between pseudo-stem and pseudo-suffix modulates the M170 for pseudo-affixed words, as for truly affixed words. The results of this experiment confirm this prediction. In addition, surface form frequency for these words also modulates the M170, providing some support for dual route recognition for words for which decomposition is a garden path.

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1. Introduction

Many recent electrophysiological experiments have investigated the role of the inferior temporal cortex (IT) in visual word recognition, including the areas identified from fMRI studies as the Visual Word Form Area (VWFA). On the one hand, evidence suggests that the VWFA functions prelexically, with detection limited to statistical properties of letter strings (Cohen et al., 2002). Work by Tarkiainen, Helenius, Hansen, Cornelissen, and Salmelin (1999) suggests that responses from the occipito-temporal cortex around 150 ms post-stimulus onset are sensitive to the difference between letters and symbols but not between, e.g., consonant strings and words. Additionally, the VWFA does not distinguish between words and pseudo-words, or between words belonging to different semantic categories (Dehaene, Le Clec, Poline, Le Bihan, & Cohen, 2002). On the other hand, the work of Pulvermüller, Assadollahi, and Elbert (2001) implicates full lexical access by 200 ms post-stimulus onset, with responses plausibly from inferior temporal areas sensitive to lexical frequencies. Solomyak and Marantz (2009, 2010) suggests that the VWFA is aptly named since a ~170 ms response from the IT including the VWFA is sensitive to statistical properties of the visual forms of words but not to their lexical entries. The present study extends this research to the pseudo-affixed words like brother, which masked priming studies (Rastle, Davis, & New, 2004) have shown to be decomposed at early stages of visual word recognition. If the VWFA analyzes word forms independent of lexical entries, then we should see evidence for morphological decomposition at the M170 for these pseudo-affixed words, as well as evidence for recognition of the word form of the whole pseudo-affixed word, should decomposition for such words truly be a garden path toward recognition. Our results confirm these predictions and argue that the IT might more properly be named a visual morpheme form area, rather than a VWFA, since it apparently uses the forms of stems and affixes to accomplish morphological decomposition as hypothesized by full decomposition models of lexical access.

This study addresses the nature of morphological decomposition during the early stages of visual word recognition. Models of visual word recognition that posit either obligatory or conditional morphological decomposition before lexical access describe the route to lexical access in terms of three distinct stages that unfold...
within the first 400 ms after viewing a word. The first stage detects orthographic properties such as letters and letter sequences. The second stage decomposes words into their morphological constituents through stem and affix stripping achieved via form representations of these morphemes. The word forms of stems activate lexical entries, and by the third stage, lexical entries of the stem retrieve semantic properties of the word. Dual route (or partial decomposition) models theorize the role of the second stage differently from obligatory decomposition models regarding whether morphological decomposition is always required for complex word recognition. Dual route theory conceptualizes decomposition as optional for word recognition because lexical representations exist both for (some) whole words and for morphological units (Hay & Baayen, 2005). Decomposition is the effective path to whole word recognition only when the saliency or availability of the stem in the complex word surpasses the saliency or availability of the whole word form. Strict obligatory (or full) decomposition theories argue against representation of whole words that might be accessed via decomposition and view decomposition as an automatic and fundamental stage of word recognition for all morphologically complex words (Taft & Forster, 1975). More moderate versions also view decomposition as obligatory but allow for both whole word and morphologically decomposed representations. Although disagreement exists regarding the overall influence of morphological properties on lexical access, models of early decomposition agree that morphological decomposition is at least partially involved in complex word recognition. On the other hand, late decomposition models put effects of morphological structure after whole word lexical access to the lexical entries of these complete words (Marínkovíc, 2004).

Early obligatory decomposition is supported by findings from masked priming studies (Rastle et al., 2004). In masked priming, a prime flashes briefly before the presentation of a target stimulus. Masking of the prime by the target prevents conscious processing of the prime, but the prime does affect target recognition. This technique is thought to activate low level processing of the prime that does not advance past the stage of morphological parsing (Forster, 1998). Masked priming studies provide evidence that morphologically complex words are obligatorily decomposed prior to visual word recognition, consistent with this interpretation. Findings from masked priming also indicate that pseudo-affixed words (e.g., brother) are parsed just like true-affixed words (e.g., worker) (Rastle et al., 2004). In a lexical decision task involving (masked) affixed words and target stems, Rastle et al. (2004) investigated the effect on response time of a stem’s semantic, morphological, and orthographic overlap with the prime whole word form. The study found facilitation effects in a transparent condition where target stems and true-affixed words were semantically and morphologically related (e.g., worker-work) and in an opaque condition, where target stems were semantically unrelated to pseudo-affixed words but shared an apparent morphological overlap (e.g., brother-broth). Effects were not found however in an orthographic condition where stems and words were only orthographically related (e.g. brothel-broth) and thus the prime could not be exhaustively parsed into the stem and a suffix. These findings suggest that morphological properties are detected before lexical ones, and that decomposition is based on visual word forms of stems and affixes rather than on orthographic features.

Results from masked priming studies indicate obligatory decomposition for all words that can be exhaustively parsed into a stem and an affix. Response time measurements have indeed provided valuable insight into lexical access; however, they often fail to exhibit effects from form frequency measures including base frequency, and, more crucially, from the transition probability from stem to affix (described later; see Solomyak & Marantz, 2010). Experiments pairing lexical decision with simultaneous MEG can produce precise information about the temporal stages of visual word recognition and relate these stages to brain areas whose properties have been revealed via lesion methods and fMRI, as in Gold and Rastle’s (2007) fMRI study of masked priming. They identified uniquely morphological priming effects in the middle occipital gyrus, where the neural response was modulated by properties of pseudomorphological prime-target pairs (e.g., corner-corn) but not by orthographic properties from orthographically overlapping pairs (brothel-broth) or by semantic properties from semantically related pairs (bucket-pail).

MEG studies of lexical access have found that brain responses to orthographic, morphological, and semantic properties can be linked to specific brain regions within specific time windows (Salmenlin, 2007; Solomyak & Marantz, 2009, 2010). The response associated with orthographic feature detection appears in the posterior occipital region at about 100–130 ms post-stimulus (the MEG M130, Solomyak & Marantz, 2010), apparently the same MEG response component associated with low level visual feature recognition called the Type I response, which is modulated by increasing pixel noise and letter-string and symbol-string length (Tarkiainen et al., 1999). The M130 response detects statistical regularities of letter strings with no apparent distinction between morphological and orthographic form (Solomyak & Marantz, 2010).

A response associated with morphological detection originates from a region of the inferior temporal cortex including what has been identified as the VWFA at about 150 ms post-stimulus (the MEG M170; Solomyak & Marantz, 2009, 2010) and shares similarities with a component that differentiates between symbol and letter sequences known as the Type II response (see Tarkiainen et al., 1999). In particular, the field patterns, latency, and source localization of the M170 are consistent with those reported for the Type II response. Evidence of visual word form detection at the M170 response is reported in two recent MEG studies of visual word recognition (Solomyak & Marantz, 2009, 2010). The first study found evidence supportive of late lexical access models that posit contact with visual word forms prior to access of lexical entries that connect form and meaning. The study employed heteronyms (words that are spelled the same but pronounced differently, e.g., wind in the sense of a breeze, or wind as in the sense of twist or turn) to examine differences between word form and lexical properties on brain activity in different regions and time-windows. The word form variables elicited early effects in the VWFA (the M170), while the lexical ambiguity of heteronyms had effects at a later response (the M350; see below). Solomyak and Marantz conducted a second study to explore the morphological and orthographic factors behind the word form effects on the M170 response (2010). The study employed bi-morphemic stimuli with free-stems (e.g., tax-able) and bound-roots (e.g., tolerable) to examine effects from morphological variables and corresponding orthographic variables on early stages of visual word recognition. Specifically, they compared effects from morphological affix frequency (frequency of the affix as a morpheme) and orthographic affix frequency (frequency of the letter string appearing at the end of a word), and also lemma transition probability (the probability of encountering the suffix given the stem) and bigram transition probability (the probability of encountering a particular letter string in the suffix given the last two letters of the base). They found early effects across word classes from the two morphological variables on M170 activity, while only the orthographic variables modulated the earlier M130 response. The lemma transition probability effect across the word classes is of particular importance because it indicates parsing attempts on all words based on the word forms of stems and affixes, as predicted by the full decomposition theory.

In its field distribution, the M170 response resembles a component modulated by masked priming in MEG and ERP peaking at
around 250 ms after presentation of the target stimulus (Monahan, Fiorentino, & Poeppel, 2008; Morris, Frank, Grainger, & Holcomb, 2007). This evoked response component parallels reaction time in its sensitivity to morphological features of the stimuli from Rastle et al. (2004) across the three stem-word conditions for true-affixed, pseudo-affixed, and non-affixed prime words (described earlier). Interpretations of results from priming experiments require a theory of the priming task, which we will not attempt here, and comparison of the present experiment with the masked priming experiments in any case is complicated by the fact that the masked priming experiments measure responses to the stems of words while we are looking at the response directly to the stimuli used as primes in these experiments. If the 250 ms response in masked priming is actually coming from the same brain region as the M170 and reflecting the same computations associated with this region, we do not know why the response is delayed in the masked priming paradigm.

Lexical access is indexed by a response in the superior temporal and Sylvian Fissure region that often peaks approximately 350 ms post-stimulus onset (the MEG M350; Pykkänen & Marantz, 2003; Solomyak & Marantz, 2009, 2010). The M350 is modulated by the ratio of the frequency of the meanings of two-meaning homonyms. The M350 response reflects a stage of word recognition where word forms are mapped to entries in the mental lexicon, which in turn activate semantic properties. These three brain responses, the M130, the M170, and the M350, parallel the stages of word recognition postulated by models of early morphological decomposition and are therefore an ideal testing ground for tracking the stages of visual word recognition for pseudo-affixed words like brother. The present study attempts to build on previous MEG research on lexical access by exploring the effects of pseudo-affixed words on brain activity during a lexical decision task with simultaneous MEG recording. We focus primarily on morphological decomposition at the M170 response in examining effects from word form frequency measures on brain activity, with special emphasis placed on the transition probability from stem to suffix.

1.1. Transition probability

We define transition probability as the chance of encountering a whole word, (e.g., farmer) given the base (e.g., farm); it is calculated here by dividing a word’s surface frequency (e.g., frequency of farmer) by its lemma frequency (e.g., the sum of all words containing farm; for the pseudo-affixed words, the transition probability from stem to suffix is estimated by the surface frequency of the pseudo-affixed form divided by the lemma frequency of the pseudo-base plus the surface frequency of the pseudo-affixed form). Transition probability (or relative frequency) is thought to regulate decomposition, having a greater influence on decomposition than the absolute frequency of the base or the whole word (Hay, 2001). Some processing models theorize that semantic transparency relates inversely to lexical/absolute frequency. Under this assumption, it is more difficult to determine the meaning of a higher frequency item based on its morphological parts, and so directly accessing a full form representation might be advantageous to recognition for high frequency derived words. Hay (2001) proposed instead that the frequency of an item relative to its base (known as relative frequency or transition-probability) predicts the mode of lexical access better than the absolute frequency. The theory assumes that if dual routes compete during recognition based on frequency, and if representations are in place for both lemmas and derived forms, it follows that the relative frequency of the lemma and the whole word should modulate the competition between the routes during recognition. Therefore, a lower relative frequency whole word like senility may be accessed from its relatively higher frequency lemma senile, while a higher relative frequency whole word like question would be accessed directly rather than from its lower frequency base quest. Solomyak and Marantz (2010) suggest that a full decomposition theory would also expect transition probability to effect decomposition, except that the decomposition route would always be the path to lexical access. That is, the higher the frequency of the whole word relative to the frequency of the lemma, the stronger the competition between a potential whole word visual word form and the (correct) parsing into stem and affix. The Hay model predicts the suppression of the decomposition route for words with relatively high whole word frequencies, leading to a diminution in the competition between the routes, while the full decomposition model predicts continued competition between whole word and decomposed analyses for the words with relatively high whole word frequencies. The transition probability effects in Solomyak and Marantz (2010) were argued to support the continued competition effects for words with high transition probabilities, and the lemma frequency effects for derived words at the M350 in that study further supported the proposal that these words are recognized via decomposition. If decomposition occurs prelexically, pseudo-morphologically complex words like brother – just like the truly affixed words with high transition probability between stem and suffix – should demonstrate transition probability effects at the M170.

Previous MEG research finds correlations between M170 brain activity and transition probability values of both free-stem words (e.g., predictable) and bound-root words (e.g., tolerable), but the M170 is not influenced by the surface frequency of these complex word forms (Solomyak & Marantz, 2010). The transition probability effect in lieu of a surface frequency effect supports a strong model of obligatory decomposition, but only from a null result. More statistical power from additional items and subjects might have revealed a surface frequency effect. The present study explores effects from pseudo-affixed words on brain activity with the following three measures of form frequency: surface (whole word form) frequency, base (orthographic stem) frequency, and transition probability. Obligatory decomposition in its strong form predicts only transition probability effects, with consistent attempts to parse the base and pseudo-affix of every word, while weaker versions would predict simultaneous surface frequency effects but only for mono-morphemic words including pseudo-affixed words like brother. Dual route theories that posit full form representations of all words also predict simultaneous effects; however, the null result in Solomyak and Marantz (2010) provides some evidence against this theory, as surface frequency effects were not found for complex words. If full form representations are available for non-decomposable words, they should be evident in modulation of brain responses by surface frequency values of pseudo-affixed words like brother.

2. Methods

2.1. Design and stimuli

Brain responses from four males and seven females (mean age = 23.6) were collected during a visual lexical decision task with simultaneous MEG recordings. All subjects were right-handed native English speakers with normal or corrected-to-normal vision and were undergraduate students at New York University. A 157-channel axial gradiometer whole-head MEG system (Kanazawa Institute of Technology, Kanazawa, Japan), recorded the MEG data continuously at a sampling frequency rate of 1 kHz. The data were filtered during acquisition between DC and 200 Hz.

In addition to 78 pseudo-affixed words of interest to the present paper, the stimulus set also included 578 non-words and 500 filler
monomorphic homographs from an experiment not reported here. The pseudo-affixed words were selected from the English Lexicon Project (ELP) (Balota et al., 2007). All words coded by the ELP as being mono-morphemes were first extracted from the ELP database. An automated procedure was then used to find the pseudo-affixed words in this list. The first step of this procedure consisted of searching for all words in the list whose last letters matched one of the nine suffixes (-able, -al, -ant, -ary, -ate, -er, -ic, -ion and -ity) from Solomyak and Marantz’s (2010) experiment. Each word’s pseudo-suffix was then stripped off in order to determine whether or not the remaining letters (i.e., the pseudo-stem) also formed a word. The words selected for the experiment were those whose pseudo-stems also formed words contained in the original list of mono-morphemes (e.g., brother, which can be parsed orthographically into the pseudo-stem broth and the pseudo-suffix -er). This list was further narrowed to words meeting length restrictions (5–8 letters, 1–3 syllables), and then items were eliminated unless there were at least seven for a given affix. All remaining items were used in the experiment; there was no selection from the list derived in this way from the ELP corpus. The final set of pseudo-affixed words ended in one of the four following suffixes: -al (n = 9), -er (n = 55), -ic (n = 7), or -ion (n = 7). The target stimuli are listed in the Appendix.

The target items, filler words, and non-words were distributed across five different lists, each consisting of 13–16 target items, 84–87 filler items, and 100 non-words (230–232 items in each list). During each of the randomized blocks, 200 total items were selected from a corresponding list of 230–232 randomly ordered items. During a typical block, subjects viewed about 14 target items, 86 filler items, and 100 non-words. Each trial began with a fixation cross appearing for 500 ms, followed by a random stimulus appearing only 750 ms due to an equipment failure. One subject viewed all items from all blocks (n = 1156). Due to time constraints, we reduced the total number of trials so that the next subject viewed 1124 items. Later, we reduced the total number of trials down to 1000. One subject viewed only 750 items due to an equipment failure.

2.2. Behavioral data processing

The exclusion procedure used in Solomyak and Marantz (2009) was applied to the behavioral data. The filler and non-word trials were not included in the behavioral analysis. First, the response time (RT) values from all of critical trials from all of the subjects were extracted. Trials with incorrect responses (constituting approximately 13% of the data) and those with RT values over 5 s long (n = 3) were excluded from the data. The remaining trials were normalized into z-scores for each subject. Trials were further excluded if the subject’s response time exceeded three standard deviations from the subject’s overall mean. The 626 trials that survived the exclusion procedure had a mean response time of 718 ms. The exclusion procedure described above applied only to the behavioral analyses.

2.3. MEG data processing

MEG data processing was the same as described in Solomyak and Marantz (2009, 2010). The Continuously Adjusted Least-Squares Method (CALM; Adachi, Shimogawara, Higuchi, Haruta, & Ochiai, 2000) was applied using the software Meg160 (Yokogawa Electric Corporation and Eagle Technology Corporation, Tokyo, Japan) to noise-reduce the MEG data and data from three MEG sensors located away from the subjects’ heads. Next, the data were imported into MNE (MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA) for further processing. Each subject’s structural MRI was reconstructed in FreeSurfer (CorTechs Labs, Inc., LaJolla, CA) and then processed in MNE to ground a cortically constrained minimum-norm analysis. A source space of 5124 activity points was created on each reconstructed surface. The BEM (boundary-element model) method was employed on activity at each source to calculate the forward solution (the magnetic field estimated at each MEG sensor). Using the grand average of the data for all trials within subjects, the inverse solution was computed from the forward solution to determine the most likely distribution of averaged MEG data over space and time. Data were then transformed to noise-normalized dSPM (dynamic statistical parameter map) values (see Dale et al., 2000). Each subject’s brain was morphed to a standard brain to compute the grand average activation across all subjects and trials (pictured in Fig. 1 at 100 ms intervals), which was then projected on the standard brain in order to identify regions of interest (ROIs). While previous procedure has been to identify ROIs based on peaks in the grand average activation over all trials and subjects (as done in Solomyak & Marantz, 2009, 2010), the present study computed the grand average activation over non-word trials only, so that ROIs were based on peaks in grand average non-word trial activation over all subjects. Identification of ROIs was thus independent of the data on which our statistical analyses are based. The vertices of each ROI were stored in label files that were subsequently morphed back to individual brains. Within each non-word based ROI, each subject’s raw MEG was computed across all trials for the inverse solution and converted into Matlab readable files. Trial-by-trial activity within ROIs was normalized within each subject for correlations with stimulus variables. The M170 ROI consisted of 293 activity points (32 points in the more posterior patch and 261 in the more anterior patch) and the M350 ROI consisted of 311 activity points (86 points in the more inferior patch and 225 in the more superior patch). All sources within the ROIs were included in the correlational analyses.

The M170 response was characterized by a peak in positive grand average activity (activation directed outwards from the cortical surface) in the occipito-temporal fusiform gyrus region of the left-hemisphere at approximately 150 ms and later at about 210 ms post-stimulus onset (see Fig. 2 for the M170 ROI and average time-course of activation over non-word trials). The M350 ROI was based on grand average negative activation (current flow directed inward from the cortical surface) of non-word trials that peaked at about 225 ms, at 275 ms, and again at 355 ms in the superior temporal region and Sylvian Fissure region of the left-hemisphere (see Fig. 3 for the M350 region and average time-course of activity across non-word trials).

Extreme response time and error trials were not excluded from the MEG analyses. Each subject’s raw MEG data was processed for extreme value counts. For each trial, data points whose value was outside two standard deviations of the overall mean were summed to produce an extreme value count for each trial. Trials exceeding these standard deviations from the overall extreme value mean were excluded (~1.45% of the data). For the remaining trials, each millisecond of ROI activity was normalized within subjects and then concatenated into a time-point by trial matrix for millisecond-by-millisecond correlations. Timing in the M170 and M350 analyses was defined in absolute terms rather than relative to individual peaks. ROI activity was correlated with the following stimulus variables: Transition probability, surface frequency, and base frequency.

Unusually low response accuracy scores among subjects indicated that the stimulus set did not take into account the typical vocabulary of undergraduate students. Thirteen of the 78
pseudo-affixed words were associated with extremely low response accuracy scores (under 60%) and were therefore excluded from the analysis. The excluded words and their accuracy scores are as follows: adder (27%), welter (33%), vestal (40%), runic (44%), titer (44%), guilder (45%), withal (50%), larder (55%), tuber (55%), gaffer (56%), glower (60%), leger (60%), and scullion (60%). From the target stimulus matrix of 735 trials, a total of 124 trials were excluded, leaving 611 trials for use in the final analysis.

The three stimulus variables were found to share a high degree of correlation that is only partly understood. Surface frequency correlates with transition probability because transition probability is partly defined by surface frequency. Transition probability is also partly defined by lemma frequency, which for the pseudo-affixed words was very similar to the base frequency (see Section 4). The correlation between surface frequency and base frequency for pseudo-affixed words is somewhat mysterious. Why should there be a connection between the frequency of a word like brother and the frequency of the morphological unrelated word broth? We checked all the obvious factors that might account for this correlation, such as shared letter or positional bi-gram frequency, but none of these factors accounted for the correlation, which we find intriguing.

Because base and lemma frequencies were almost identical for our pseudo-affixed words (since the “bases” had virtually no
morphological derivatives in our corpora), transition probability could essentially be computed from the two other variables, and all three could not therefore be used simultaneously in any analyses. To compare the present results with those of Solomyak and Marantz (2010), we were interested in contrasting surface frequency with transition probability for the M170 ROI and base frequency with transition probability for the M350 ROI. The variables were thus transformed into decorrelated values via a principle components analysis (PCA), with transition probability orthogonalized against surface frequency and separately against base frequency. For the M170 analyses, then, we could compare the effects of decorrelated (transformed) surface frequency and transitional probability measures, while for the M350 we could compare the effects of decorrelated (transformed) base frequency and transition probability measures. Intercorrelations between the original and transformed variables are provided in Table 1.

Time-course analyses were conducted to examine the influence of individual stimulus variables on the change in millisecond level activity over time. The analyses computed correlations between activity at each time-point and the individual stimulus variables. The M170 time-course analysis involved the transformed values for transition probability against surface frequency, and original values of base frequency, while the M350 time-course analysis involved the transformed values for transition probability against base frequency, and the original surface frequency. In light of the numerous regressions computed in the analysis, a multiple comparisons correction procedure (a permutation test following Maris & Oostenveld, 2007) was performed on continuous temporal regions of the point-by-point regressions of the individual correlation waves that exceeded the .05 significance level prior to correction. Correlation coefficients of consecutive effects at the \( r = .05 \) significance level were summed together to create a statistic \( \sum r \). The \( \sum r \) statistic’s significance at each temporal cluster of significant effects was tested by computing a Monte-Carlo \( p \)-value as follows: The correlation wave was computed for 10,000 random permutations of the independent variable. The \( \sum r \) statistic was then computed at each of the 10,000 random permutations of the original correlation wave at each temporal cluster of consecutive significant effects. The highest absolute \( \sum r \) value at each permutation of the independent variable was taken to create a distribution of individual \( \sum r \) values for comparison with the original value. Finally, the Monte-Carlo \( p \)-value was defined by computing the percentage of new values higher in absolute value than the original statistic.

### 3. Results

#### 3.1. M170 analyses

Time-course analyses were performed to explore effects of individual stimulus variables on M170 activity between 140 and 220 ms. The time window was chosen to include the two peaks in the M170 ROI’s grand average activation over non-word trials at 150 ms and 210 ms. Positive effects from transition probability were found between the 164–208 ms range (\( \sum r = 4.5852 \) for 45 time points, \( p < .0001 \) following correction for multiple comparisons), indicating that greater transition probability was associated with stronger M170 activation. Surface frequency exhibited positive effects on M170 activity between the 161–173 ms time range (\( \sum r = 1.3021 \) for 12 time-points) but this effect was not significant following correction for multiple comparisons (\( p < .095 \)). Higher values of base frequency were associated with weaker M170 activation, but the correlations only approached significance between 182 and 198 ms (\( \sum r = 1.6147 \) for 17 time points, \( p = .0584 \) following correction for multiple comparisons). An additional analysis was conducted on surface frequency and M170 activity averaged over a 150–180 ms time window (based on the peak of the correlation wave from the time-course analysis). Surface frequency was found to exhibit significant effects on the amplitude of the averaged activity, with greater values of surface frequency again indicating stronger (more positive) M170 amplitude (\( r = .0915 \), \( p = .0238 \); we also found significant effects of surface frequency on activity averaged over the original 140–220 ms time-window). Right-hemisphere analyses of M170 activity did not yield statistically significant results.

#### 3.2. M350 analyses

M350 time-course analyses were conducted on activity between 220 and 320 ms based on an a priori decision to restrict the time window to 100 ms.\(^2\) Significant effects from base frequency were found between 239 and 259 ms (\( \sum r = 2.2432 \) for 21 time points, \( p = .0303 \) following correction for multiple comparisons). The positive correlation of base frequency with negative activity means that higher values of base frequency were associated with weaker activity. Transition probability and surface frequency were not significantly correlated with M350 activity following correction for multiple comparisons. The stimulus variables were not significantly correlated with right-hemisphere M350 activity. Correlations with ROI activity and the relevant variables are plotted in Fig. 4.

#### 3.3. Mixed effects model analyses

We additionally conducted a mixed effects model analysis of ROI activation with subjects and items as random factors and bigram frequency and length as fixed factors. The \( p \)-values were calculated based on the \( t \)-values and tested against 10,000 permutations. M170 activity was significantly correlated with transition probability at \( p < .002 \), but not with surface frequency at \( p > .148 \). M350 activity was again significantly correlated with base frequency at \( p < .031 \).

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\(^2\) Earlier activity associated with the M250 time window was included in the M350 analysis because the M250 resembles the M350 in terms of magnetic field and superior temporal location (Py ttkanen, Stringfellow, & Marantz, 2002). Therefore, M250 effects cannot be excluded.

### Table 1

Intercorrelations between original and transformed variables.

<table>
<thead>
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<th>Variable</th>
<th>SF</th>
<th>TP</th>
<th>BF</th>
<th>PCA-SF against TP</th>
<th>PCA-TP against SF</th>
<th>PCA-BF against TP</th>
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\( TP = \) transition probability, \( SF = \) surface frequency, \( BF = \) base frequency. PCA variables were orthogonalized against original variables.
Plots of the t-values, estimates, and p-values (tested against 10,000 permutations of the independent variable) from the mixed effects models are presented in Fig. 5.

3.4. Behavioral analyses

Behavioral analyses were conducted to determine effects from individual stimulus variables on subjects’ response time (RT). Surface frequency was found to have a facilitatory effect on RT as higher values of surface frequency were associated with lower values of RT ($r = -0.1240$, $p = .0019$). None of the other stimulus variables were significantly correlated with RT.

4. Discussion

Solomyak and Marantz (2010) found that the VWFA performs obligatory decomposition of morphologically complex words that can be exhaustively parsed into a stem (whether bound or free) and a suffix, with the transition probability between stem and suffix modulating the amplitude of the response during the M170 time window. The present study explores this result by examining the M170’s response to pseudo-affixed words. If morphological decomposition is based on visual word forms rather than on lexical entries, pseudo-affixed words with only apparent morphologically complexity such as *brother* should yield the same decomposition effects at the VWFA as those found for truly complex words in Solomyak and Marantz (2010). The present findings confirm this prediction as stronger amplitude at the M170 was correlated with higher values of transition probability.

Some additional findings from this study are of particular interest for models of visual word recognition as well as for the interpretation of previous findings from the evoked response literature. First, unlike the true-affixed words in Solomyak and Marantz (2010), the pseudo-affixed *brother* words of the present study yielded a significant effect of surface frequency on amplitude of averaged M170 activity. This finding supports parallel dual route models that predict simultaneous decomposition and whole word effects during visual word recognition. Full decomposition models could be strengthened if future work confirms that surface frequency effects at the M170 are only present for words like *brother* for which the decomposition route is completely unmotivated (a true garden path) while always absent for truly affixed words like *worker* for which decomposition is possible (including those words for which decomposition yields bound roots as in *tolerable*). In particular, to address theories like that of Hay (2001) that suggest that words with high transition probabilities from stem to suffix (words with high suffix dominance) would be recognized as wholes, rather than through decomposition, further research could confirm a difference in surface frequency effects at the M170 between such words and the pseudo-affixed words, which should be recognized as wholes according to all models under discussion.

Second, although the present findings replicate the result from Solomyak and Marantz (2010) that the base frequency of apparently morphologically complex words modulates the early portion of the M350 response, the effects in these two studies go in opposite directions. For the truly affixed words in Solomyak and Marantz (2010) that should arguably decompose in recognition, higher base frequency values correlate with higher amplitude activation. In contrast, for the pseudo-affixed words (whose decomposition is unmotivated), higher base frequency correlates with lower amplitude activation. Solomyak and Marantz (2010) attributed their effect to the (derivational) family frequency of the true-affixed words rather than their pure base frequency (e.g., for a word like *taxable*, the family frequency is the summed frequency of all words with *tax* as a base, whereas pure base frequency is the surface frequency of the orthographic form of *tax* as an independent word). It is important to note that the bases of the pseudo-affixed words in the present experiment generally have no derivational families. The average base frequency to lemma frequency ratio of the free-stem affixed words in Solomyak and Marantz (2010) is approximately .52, compared to a ratio of about .99 for the pseudo-affixed words in the present experiment. To illustrate, the pseudo-affixed word *mutter* does not have derivational families as the base *mutter* is only found in *mutter* in our corpora and not in any other word. This suggests that the facilitatory effects of frequency – lower amplitude responses with higher frequency stimuli – at the M350 may only be found for items with no derivational families, whereas for words with many derivational family members the inhibitory effects from family frequency – higher amplitude responses with higher family frequencies – may overwhelm effects of simple base frequency. It should be noted that the ERP and MEG literature provide conflicting predictions about the
relationship between base frequency and M350 amplitude. The ERP literature generally reports findings of decreased N400 amplitude with increased frequency values (Marinkovic, 2004), while the MEG literature reports increased M350 amplitude with increased lemma frequency (Pykkänen, Feintuch, Hopkins, & Marantz, 2004; Solomyak & Marantz, 2010).

Third, Vinckier et al. (2007) have suggested that the more anterior regions of the temporal lobe are associated with more abstract representations. To explore this hypothesis, we performed a more restrictive analysis of the M170 ROI. As Fig. 1 illustrates, our M170 ROI is comprised of two brain regions, one smaller and more posterior than the other. The initial M170 ROI was based on general prior assumptions about the M170 response – we were looking for regions along the inferior temporal lobe with a positive peak in average activity between the 140–220 ms time window. These criteria resulted in the initial M170 ROI that involved two discontinuous regions of coinciding brain activity. The post hoc analysis divided the M170 ROI based on anatomy into two restricted ROIs, each of which was a continuous brain region – one larger more anterior ROI and one smaller more posterior ROI. The restrictive ROI analysis examined effects from the individual stimulus variables on each of the restricted ROIs. Time-course analyses of the more posterior ROI failed to yield significant effects from the stimulus variables, although the correlation with surface frequency only approached significance. A significant surface frequency effect was found in an analysis of average M170 activity over the 150–180 ms window ($r = .0895$, $p = .027$). For the more anterior ROI, a time-course analysis yielded an effect of transition probability between 168 and 208 ms ($P = 4.32$ for 31 time points, $p = .001$, following correction for multiple comparisons). Significant effects were not found for the other variables, although a time window analysis of surface frequency and averaged M170 activity over the 150–180 ms window yielded a significant correlation ($r = .0821$, $p = .0424$). The restriction of transition probability effects to the more anterior region supports the association between the “anteriorness” of the region and the “abstractness” of the

Fig. 5. Plots of t-values, estimates, and p-values tested against 10,000 permutations of each variable from the mixed effects model.
computations, since the transition probability effects depend on activation of relatively abstract word form representations of morphemes rather than simply constructs of n-grams. For form representations, a surface frequency effect can be seen as a high n-gram effect. This is a relatively concrete representation, while a transition probability effect is associated with relatively abstract representation, a connection between visual word forms of morphemes. It should be noted here that we should not be interpreted as making any strong claims about the precision of the localizations of these effects.

Fourth, we wanted to determine whether the effects found for functionally defined labels would also be found for anatomical labels from Desikan et al.’s (2006) brain parcellation scheme. For the anatomical analysis, we used the fusiform label for comparison with the M170, and the superior temporal label for comparison with the M350 label. Time-course analyses were conducted on fusiform activity over the 140–220 ms time window. Transition probability effects were significant between 163 and 202 ms ($\sum r = 4.0466$ for 40 time points, $p = 0.0017$ following correction for multiple comparisons). Surface frequency effects were found between 162 and 172 ms, but were not significant following correction for multiple comparisons. Analyses of superior temporal activity over the 220–320 ms time window yielded significant base frequency effects between 236 and 255 ms ($\sum r = 1.9138$ for 20 time points, $p = 0.0381$ following correction for multiple comparisons).

Fifth, to examine whether the results were influenced by sublexical variables, we regressed mean bigram frequency and length onto the individual stimulus variables, and re-ran the time-course analyses with the residuals from each regression. The M170 analyses were again conducted on activity between 140 and 220 ms. The new residual transition probability had positive effects between 160 and 209 ms ($\sum r = 5.2576$ for 49 time points, $p = .0004$ following correction for multiple comparisons). The residual base frequency had negative effects on activity between 239 and 261 ms ($\sum r = 2.4214$ for 20 time points, $p = .0217$ following correction for multiple comparisons). The correlation waves are shown in Fig. 6.

On a final note, recall that our experimental items were all the items from the ELP that fit certain criteria. As a result, given the relative frequency of English affixes, we used a set of pseudo-affixed words dominated by those ending in -er. Therefore, one might ask whether the -er words drove our transition probability results, as these words constituted over half the stimulus set (about 72% of target trials following exclusion procedures). We therefore separated the -er trials from the non -er trials, orthogonalized the original transition probability values against the original surface frequency values for each set, and employed the transformed transition probability variables in individual time-course analyses over the 140–220 ms time-window. For both the -er words ($n = 433$) and the non -er words ($n = 178$), higher values of transition probability were associated with stronger (more positive) M170 activation. For the non -er set, the correlation was significant between 181 and 205 ms ($\sum r = 4.9598$ for 25 time points, $p = .0110$, following correction for multiple comparisons). The correlation for the -er set was also significant between 159 and 177 ms ($\sum r = 2.4799$ for 19 time points, $p = .037$ following correction for multiple comparisons).

5. Conclusion

The present findings taken with those in Solomyak and Marantz (2010) support an obligatory decomposition model of complex word recognition whereby the VWFA decomposes all words based on their visual word forms and on the statistical correlations between forms of affixes and stems. Lexical entries appear to play no role in preventing decomposition for the brother words. The surface frequency effects in this study suggest that whole word visual representations may exist for non-decomposable words like brother. Parallel dual routes may therefore be in effect, but only for those words like brother whose pseudo-stems represent morphologically unrelated information. The two primary findings from the present
study and Solomyak and Marantz (2010) are that decomposition is obligatory and based on statistical relations between stems and affixes, and that whole word representations may be available early in word visual word recognition, but only for those words whose decomposition does not lead to recognition in the mental lexicon.

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Appendix A. Supplementary material


References


