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Evidence for Morphological Composition in Compound Words using MEG

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Morphologically complex words in the mind/brain

2 **ABSTRACT**

3 Psycholinguistic and M/EEG studies of lexical processing show convergent evidence for
4 morpheme-based lexical access that involves early decomposition into constituent morphemes
5 and later combinatorial semantic operations. Considering that both semantically transparent
6 (e.g. sailboat) and semantically opaque (e.g. bootleg) compounds undergo decomposition at
7 the earlier stages of lexical processing, subsequent combinatorial operations should account
8 for the difference in the meaning retrieval of these different word types. In this study we use
9 magnetoencephalography (MEG) to pinpoint the neural bases of this combinatorial stage in
10 English compound word recognition and production. MEG data were acquired while participants
11 performed a word naming task in which three word types (transparent, opaque, and simplex)
12 were contrasted in two priming conditions (repetition and constituent). Analysis of onset latency
13 reveal shorter latencies to speak for compound words than simplex words when primed,
14 providing evidence of morphological decomposition. Analysis of associated brain activity have
15 uncovered a region of interest implicated in morphological composition, the Left Anterior
16 Temporal Lobe (LATL). Previous studies using sentences and phrases have highlighted the
17 LATL as performing computations for basic combinatorial operations. Results are in tune
18 with decomposition models and suggest the existence of a lexical processing dynamic that is
19 modulated by morphological complexity for parsing structure and by semantic transparency for
20 constructing meaning.

21 Keywords: compounds, MEG, left anterior temporal lobe (LATL), word naming, morphology, semantic transparency, morphological
22 decomposition, morphological composition

1   INTRODUCTION

23 Some words are simple and some words are not. This, at first, sounds like a very trivial tautology, but the
24 controversy over whether multi-morphemic words are simply stored in whole word form (**Butterworth**,

1983; **Giraudo and Grainger**, 2001) or always constructed from their morphemic parts has been entertaining, provocative, and contentious in the field of lexical processing for the last forty years (**Rastle and Davis**, 2003). A comprehensive description of how words are both stored and retrieved requires the understanding of how form and meaning are connected, and how this connection unfolds in time in natural speech. Understanding the mechanisms involved in the comprehension of linguistic expression involves examining how perceptual information is analyzed from the moment in which the input is presented until the activation of the intended meaning happens.

The potential contrast between simplicity and complexity in word storage and retrieval was first discussed in the classic affix-stripping model (**Taft and Forster**, 1975), which proposed that lexical access always proceeds via the stem of morphologically complex words. Taft and Forster showed that pseudo-complex words with real stems took longer to reject in a lexical decision task (and were often selected incorrectly as words), than pseudo complex words in which a real prefix was followed by a non-existent stem. This was very early evidence that structure within a word matters, and is consulted online in particular to achieve lexical access. The evidence has mounted both in favor (**Taft**, 2004; **Marslen-Wilson, Tyler, Waksler, and Older**, 1994; **Rastle, Davis, and New**, 2004) and against full decomposition (**Butterworth**, 1983; **Giraudo and Grainger**, 2001), but the arguments against morphological sensitivity in lexical access have lost ground in the light of mounting evidence, giving rise to processing models where morphological decomposition is a necessary stage in processing. These psychological models make a variety of predictions as to the stages and time-course of lexical access, but there is a lack of evidence for the anchoring of the stages in particular areas of the brain. This study seeks to identify the area responsible for the composition of morpheme meanings. This area should be sensitive only to the composition within complex words whose morpheme meaning have a *transparent* semantic relationship to the overall meaning as compared to complex words whose morphemes do not share a semantic relationship, *opaque*.

One way to look at lexical processing is to see if activating morphological structure can modulate the accessibility of a complex word. Some cross-modal priming studies (**Marslen-Wilson et al.**, 1994) showed that priming in lexical decision between words that shared a stem only occurred when the prime and target had related meanings (e.g., departure primed depart but department did not) while other studies (**Zwitserlood**, 1994) found that priming did not depend on a semantic relationship between the prime and target. However, masked priming studies that manipulate semantic transparency quite generally find facilitation effects regardless of whether prime and target share the same morphological root (**Rastle, Davis, and New**, 2004; **Longtin, Segui, and Hallé**, 2003; **Fiorentino and Poeppel**, 2007; **McCormick, Rastle, and Davis**, 2008). Facilitation effects are found for every complex word that can be segmented in existing morphemes, which means that masked prime/unmasked target pairs like *corner-corn* and *bootleg-boot* speed recognition of the target facilitation as much as pairs like *cleaner-clean* and *teacup-tea*, even though there is no morphological relationship in the former pairs.

If decomposition is performed for every word that can be exhaustively parsed into the forms of existing morphemes, regardless of whether the word is indeed morphologically complex, research on visual word recognition should shift the focus from decomposition to the subsequent mechanisms engaged to activate the actual meaning of a complex target word. **Meunier and Longtin** (2007) suggest that word activation comes to play in stages, which include at least one early stage for morphological decomposition and a later stage for semantic integration of the morphological pieces. **Fiorentino, Naito-Billen, Bost, and Fund-Reznicek** (2013) presents evidence for a morpheme-based route for word activation that includes decomposition into morphological constituents and combinatorial processes operating on these representations. Since previous studies have shown that early decomposition triggered by morphological structure happens automatically for transparent and opaque words, the difference between these two word types may manifest itself during the later stage of combinatorial operations.

Another way to look at lexical processing is to look at composition. There are proposals for a general binding mechanism for basic composition proposed by **Bemis and Pylkkänen** (2011) that may play a role at the word-level between words in a phrase. In a minimum composition paradigm, (**Bemis and Pylkkänen**, 2011) found that two composable items,in an adjective-noun phrase evoked more activation

76 in the left anterior temporal lobe, LATL, than two non-composable items, a random letter string and word.
77 This was taken as evidence that the most basic of combinatorial processing is supported by the LATL.
78 This region should thus be also responsible for combinatorial operations with morphemes. Semantic
79 transparency, the degree to which the combination of morpheme meanings corresponds to the overall
80 word meaning, can be used to test whether the LATL is engaged when determining the semantic fit
81 between morphemes within a complex word. In this experiment, we will use compounds to vary the
82 semantic transparency of morphologically complex words since they consist of existing free morphemes
83 with different levels of semantic relations between constituent and whole compound meanings. Thus,
84 we expect semantically consistent word types such as transparent compounds (e.g. mailbox) to elicit
85 activity in this region greater than simple words since their meanings derive from the composition of
86 their morphemic parts, whereas we would not expect to see the same increase of activity for semantically
87 opaque compounds (e.g. bootleg) since there is no relationship between its parts and its meaning. Since
88 compounds are formed from words and have structures and meanings that resemble adjective-noun
89 phrases, this provides an interesting basis to studying effects of intralexical semantic composition as
90 an analogue to composition at the phrase level.

91   Thus, a model of complex word recognition would require at least these two stages of process: parsing
92 into basic units (decomposition), and the composition of these word forms into a complex meaning. To
93 unpack these stages, we propose using two types of priming paradigms: a partial-repetition priming,
94 similar to the ones used in masked priming studies, which will be used to investigate the decomposition
95 effects on compounds, and a full-repetition priming, which will be used to investigate the composition
96 effects on their morphemes. This study uses a word naming production task to investigate these stages
97 involved in lexical processing. This task will be done while brain activity is recorded using MEG to
98 investigate whether there is an area within the left temporal lobe that is responsible for morphological
99 composition. This study contributes to the work of characterizing the neural bases of lexical processing of
100 complex words by providing evidence for composition within compound words, while linking it to their
101 neural correlates. Given the prior literature, we expect to find evidence of decomposition for compound
102 words but not for simplex words. This would be a finding that fits in with the visual word recognition
103 literature, specifically the masked priming literature, where there are facilitatory effects when priming
104 morphologically complex words but not simplex words. However, we do not expect to find this overall
105 benefit of morphological complexity in composition. Since composition is meaning governed, we only
106 expect to find composition effects for transparent compounds in the brain activity.

2   MATERIAL & METHODS

107 *Participants.* Eighteen right-handed native speakers of English, with normal or corrected vision,
108 participated in this experiment. Three participants were excluded due to large number of trial rejections
109 caused by a noise interference (>25 %). Details for rejection are described in the procedure.

110   *Material.* All stimuli consisted of English bi-morphemic compound (e.g. teacup) and morphologically
111 simplex (e.g. spinach) nouns, matched for length and surface frequency. We manipulated semantic
112 transparency, including fully semantically transparent (e.g. teacup) words, in which both constituent
113 morphemes have a semantic relationship to the meaning of the whole compound, and fully semantically
114 opaque words (e.g. hogwash), in which neither of the constituent morphemes have a semantic relationship
115 to the compound meaning.

116   Three hundred eleven English compounds were compiled from previous studies (**Drieghe, Pollatsek,**
117 **Juhasz, and Rayner**, 2010; **Fiorentino and Poeppel**, 2007; **Fiorentino and Fund-Reznicek**, 2009;
118 **Juhasz, Starr, Inhoff, and Placke**, 2003) and categorized in terms of semantic transparency by means
119 of a semantic relatedness task conducted using the Amazon Mechanical Turk tool. In this task, 20
120 participants were asked to judge, on a 1-7 scale, how much each constituent of the compounds related
121 to the whole word. On the scale, 1 corresponded to unrelated and 7 corresponded to very related. Each
122 participant was randomly presented with one of the constituents of each compound. Compounds were

	Transparent		Opaque		Simplex	
	prime	target	prime	target	prime	target
control	doorbell	teacup	heirloom	hogwash	brothel	spinach
repetition	teacup	teacup	hogwash	hogwash	spinach	spinach
control	door	teacup	heir	hogwash	broth	spinach
partial-repetition	tea	teacup	hog	hogwash	spin	spinach

Table 1 Design Matrix

123 classified as semantically opaque (henceforth opaque) if the sum of the scores of their constituents were
124 within the interval 2-6, and as semantically transparent (henceforth transparent) if the sum were within the
125 interval 10-14. For example, the opaque compound *deadline* received a summed rating of 3.76 with *dead*
126 contributing a transparency rating of 1.44 and *line* contributing a rating of 2.32. Similarly, the compound
127 *dollhouse* received a summed rating of 11.79 with *doll* contributing a transparency rating of 6.47 and
128 *house* contributing a rating of 5.32. Sixty compounds were selected for each word type. This method
129 of semantic transparency norming and the ratings were consistent with the mentioned prior studies. The
130 morphologically simple words (henceforth simplex: e.g. spinach) were pooled from **Rastle et al.** (2004)
131 and the English Lexicon Project (**Balota, Yap, Cortese, Hutchison, Kessler, Loftis et al.**, 2007).The
132 simplex words were selected to have an embedded word within it but with no morphological or semantic
133 relationship between the embedded word and the whole word. Also, these words were constrained and
134 selected such that if the embedded word were removed, the remaining word part would have no meaning
135 or use as a morpheme.

136 *Design.* The three different word types were contrasted in two priming conditions: full repetition and
137 partial (constituent) repetition (See Table 1). For the repetition priming condition, the same compound was
138 used as prime and target (e.g. TEACUP-teacup). For the constituent priming, we used the first constituent
139 of the compound as the prime (e.g. TEA-teacup). For the simplex condition, the embedded word was used
140 as the constituent in the constituent priming condition (e.g. SPIN-spinach). These two priming conditions
141 were paired to control conditions in which the prime had no semantic relationship to the target (e.g.
142 DOORBELL-teacup; DOOR-teacup).

143 *Procedure.* All participants read all the items in all conditions (720 total), which were divided in
144 three lists of 240 words and randomized within each list. The order of presentation of the lists was
145 counterbalanced between subjects. The experimental task was word naming: subjects were presented
146 with word pairs, and they were asked to read out loud the second word of each pair. This task allowed for
147 the use of every presented item to be included in the analysis. Each trial began with the presentation of a
148 fixation cross, followed by the prime, then the target. Each of these visual presentations was presented for
149 300 ms with a 300ms blank. We recorded the onset latency to speech and the utterance from each subject
150 for behavioral analysis.

151 Before the experiment, the head shape of each participant was digitized using the Polhemus Fastscan
152 system, along with five head position indicator points, which are used to co-register the head position
153 with respect to the MEG sensors during acquisition. Electromagnets attached to these points are localized
154 after the participants are lying within the MEG sensor array, allowing for coordination of head and sensor
155 coordinate systems. The head shape is used during the analysis to co-register the head to participants
156 MRIs. For half of the participants, MRIs were not provided; therefore, we scaled the common reference
157 brain that is provided in FreeSurfer to fit the size of these participants head.

158 During the experiment, participants remain lying in a magnetically shielded room as their brain activity
159 is monitored by the MEG gradiometers. The experimental items were projected onto a translucent screen
160 so the participant could read and perform the task. The MEG data were collected using a axial whole-head
161 gradiometer system with 157 channels and three reference channels (Kanazawa Institute of Technology,
162 Nonoichi, Japan). The recording was conducted in direct current (DC), that is, without a high-pass filter,
163 and with a 300 Hz low-pass filter and a 60 Hz notch filter.

164 *Analysis.* We examined onset latency, the reaction time to speak, to evaluate the effects of morphological
165 decomposition based on (**Fiorentino and Poeppel**, 2007). Since reaction time is sensitive to lexical
166 processes, compounds should differ from single words, with processing associated with decomposition,
167 composition, as well as properties of the constituents rather than the whole word. A non-decompositional
168 account predicts no differences due to word structure, if the words are correctly matched for relevant whole
169 word properties. Thus, onset latency can be used to disentangle whether or not there is a decomposition
170 effect. The behavioral data were analyzed using traditional analysis of variance for the Word Type by
171 Partial-Repetition priming interaction model. Partial-repetition priming in lexical decision tasks has been
172 used to demonstrate the accessibility of morphemes within complex words (Rastle et al. 2004). Similar
173 behavioral effects have also been found using word naming (see Neely, 1991 for a comparative review of
174 lexical decision and word naming). Therefore, the evidence of decomposition effects can be in observed
175 in the reaction time to speak, *onset latency*. Prior research leads to the prediction that we should observe
176 a facilitative effect of shorter onset latency for the complex word types as compared to their simplex word
177 counterparts.

178 After brain data acquisition, we applied a Continuously Adjusted Least-Squares Method (**Adachi et al.**,
179 2001), a noise reduction procedure in the MEG160 software (Yokogawa Electric Corporation and Eagle
180 Technology Corporation, Tokyo, Japan) that subtracts noise from the MEG gradiometers based on noise
181 measurements at the reference channels positioned away from the head. The data were bandpass filtered
182 between 1-40 Hz using a IIR filter. The recording of the whole experiment was segmented in epochs of
183 interest, from -200 ms before to 600 ms after stimulus onset. We rejected trials in which the maximal
184 peak-to-peak amplitude exceeded the limit of 4000fT and we equalized the trials per condition for proper
185 comparison. Sensor channels were marked as bad and discarded for each subject if the channels peak-to-
186 peak rejection exceeded 10%.

187 A noise-covariance matrix was computed for each participant using an automated model selection
188 procedure citep*Engemann:2014 on the baseline epoch from -200 ms to the onset of the presentation of
189 the fixation cross. For participants with MRIs, cortical reconstructions were generated using FreeSurfer
190 resulting in a source space of 5124 vertices (CorTechs Labs Inc., La Jolla, CA and MGH/HMS/MIT
191 Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA). For participants without
192 MRIs, the headshape-constrained FreeSurfer average brain was used. A boundary-element model (BEM)
193 method was used to model activity at each vertex to calculate a forward solution. An inverse solution
194 was generated using this forward model and noise-covariance matrix, and was computed with a fixed-
195 orientation constraint requiring dipole sources to be normal to the cortical surface. The sensor data for
196 each subject was then projected into their individual source space using a cortically-constrained minimum
197 norm estimate (all analyses were conducted using MNE-Python: **Gramfort, Luessi, Larson, Engemann,**
198 **Strohmeier, Brodbeck et al.** (2013b,a)) resulting in noise-normalized dynamic statistical parameter maps
199 (dSPMs).

200 This analysis was conducted with the objective of isolating the activity related to basic computational
201 mechanisms involved in the composition of previously-activated constituent morphemes in the
202 compounds. In order to examine this mechanism, we considered the neurophysiological data related solely
203 to the silent reading of the primes in the repetition condition. The priming results also served to make sure
204 that these words were actually read by the participants, because they affected the activation of the target.
205 The composition effect was examined as if a list of isolated words were read silently by the participants, as
206 the words used as primes were assumed not influenced by their preceding trial. In this respect, the method
207 of analysis is analogue to that adopted by **Zweig and Pylkkänen** (2009), in which the authors directly
208 compare complex (derived) with mono-morphemic words, thus aiming to find decomposition effects that
209 are not dependent on priming.

210 For this analysis, our design (Table 2) reduces to the simple comparison between compounds (e.g.
211 TEACUP) and simplex words (e.g. SPINACH) of the same size that served as primes in the repetition
212 condition (e.g. TEACUP-teacup) described above in the Design section. Since, for this analysis, we
213 use neurophysiological data related to the silent reading of the words that served as primes, there is
214 no behavioral data for these words. By these means we also avoid artifacts associated with voluntary

Word Types	Examples
Opaque	hogwash
Transparent	teacup
Simplex (control)	brothel

Table 2 Primes Analysis

	SS	df	MS	F	p
Word Type	2465.48	2	1232.74	1.82	.178
Partial-Repetition Priming	17906.72	1	17906.72	25.91***	$< .001$
Word Type x Partial-Repetition Priming	3578.01	2	1789.01	9.24***	$< .001$
Total	910981.34	107			

Table 3 Onset Latency Time Differences

215 movements that can compromise the analysis of the effects of interest to the study (**Hansen, Kringelbach,**
216 **and Salmelin**, 2010).

217   We examined the neural activity localized in the entire left temporal lobe. This region was selected based
218 on composition effects found with sentences (**Friederici et al.**, 2000) or adjectival phrases (**Bemis and**
219 **Pylkkänen**, 2011). In order to verify if there was increased activity for compounds in this area, a t-test was
220 performed on the difference of a compound word type (opaque, transparent) and its simplex control word
221 from 100 ms to 600 ms after the stimulus onset. The p-value map of the brain was generated for the time
222 series and spatiotemporal clusters were identified for contiguous space-time clusters that had a p-value
223 of less than .05 and a duration of at least 10 ms. The t-values from the clusters were summed for those
224 clusters that met these criteria. Then, a non-parametric, cluster-based permutation test was performed on
225 the summed t-values within the left temporal lobe on these clusters. A distribution was computed from
226 calculating the summed t-values from clusters formed after shuffling the condition labels. The corrected
227 p-value was determined from the percentage of clusters that were larger than the original computed cluster
228 (**Maris and Oostenveld**, 2007). These tests were computed using the statistical analysis package for MEG
229 data, Eelbrain, (https://pythonhosted.org/eelbrain/).

3   RESULTS

230 **Morphological decomposition.** Behaviorally, we found a significant effect of constituent priming
231 [$F(1,17) = 25.91$, p $<.001$], but most critically an interaction of word type by constituent priming [$F(2,17)$
232 $= 9.24$, p $<.001$] (Figure 1). This effect shows that there is a greater facilitation in word naming for
233 compound words than for morphologically simple words when primed. This results show that even
234 in word production, there is sensitivity to morphological structure above and beyond orthographic and
235 phonological overlap (Table 3).

236   **Morphological composition.** Results reveal significant effects of lexical complexity identified by the
237 permutation tests on the difference of compounds to their simplex counterparts within the temporal lobe.
238 There were two significant clusters associated with the difference of transparent compounds and simplex
239 words. The first cluster was localized toward the anterior part of the left temporal lobe from 250 to
240 470ms ($\sum$ t = 4552.3, p $<.05$, Figure 2). The second cluster of activity was localized to the posterior
241 part of the superior temporal lobe from 430 to 600 ms ($\sum$ t = 5654, p $<.05$, Figure 3). However, there
242 were no significant clusters found for the difference of opaque compounds and simplex words within the
243 temporal lobe. Taken together, our results that the anterior part of the left anterior lobe is implicated in this
244 difference found between morphologically complex words and their simple counterparts. This increase in

245 activity for morphologically complex words occurs for semantically transparent compounds but not for
246 semantically opaque ones, that is, this engagement occurs for complex words whose morphemes have a
247 semantic relationship to the overall meaning of the word. This same pattern of activity seems to continue
248 as it subsequently engages in the posterior part superior temporal lobe.

4 DISCUSSION

249 Analyses of the different word types in isolation reveal very consistent evidence that there is a difference
250 in how simplex and complex words are processed in the brain. The behavioral results revealed there is
251 a stage in lexical access that is sensitive to the morphological complexity of words. The onset latency
252 interaction effect where complex words were produced faster than simple words when primed by their
253 constituent morpheme is largely consistent with the results within the masked priming literature on word
254 recognition, and gives further evidence that where there is a there is a decomposition stage in lexical
255 access where complex words are parsed into their morphemes (**Rastle et al.**, 2004; **Taft**, 2004; **Morris**
256 **et al.**, 2007; **McCormick et al.**, 2008; **Fiorentino and Fund-Reznicek**, 2009). The parsing operation
257 occurs independent of semantic relationship between constituent morphemes and their complex word.
258 Since early activation of constituents via morphological decomposition happens irrespective of semantic
259 transparency, what differentiates transparent and opaque compound must happen, thus, during a later
260 stage of morphemic composition. The increased activity found for transparent compounds in anterior
261 temporal lobe from 250 to 470ms provides evidence with stage in lexical access where meanings of
262 the morpheme play a part in access the overall meaning of the word. **Bemis and Pylkkänen** (2011)
263 show combinatorial effects on the LATL for adjectival words at around 250 ms after the critical word is
264 presented. The difference in timing could be explained by the different time points in which we time lock
265 the onset of the stimulus. In **Bemis and Pylkkänen** (2011), the onset coincides with the onset of the noun
266 *boat* in the phrase *red boat*, whereas in our study the critical stimulus is the entire compound textitsailboat.

267   The increased activation in the posterior temporal lobe for transparent compounds from 430 to 600 ms
268 that follows the activity in the LATL is consistent with the fact that this region is involved in lexical
269 retrieval (**Lau et al.**, 2008; **Hickok and Poeppel**, 2007). **Lau et al.** (2008) proposed that the posterior
270 region of the temporal lobe as the best candidate for the lexical storage of words. Since the LATL is
271 responsible for composing the meaning of the constituent morphemes, the posterior temporal lobe would
272 be responsible for retrieval information from its stored lexico-semantic representation. This region is also
273 engaged sound-to-meaning transformation (**Binder et al.**, 2000), which would include the retrieval of
274 phonological information. This study is in tune with decomposition models from visual word recognition
275 literature and provides the neural basis for a stage in lexical access involved in the composition of meaning
276 within compound words, thus helping to disentangle cognitive processes that are compressed in response
277 times alone. Bridging results from psycholinguistic research with MEG recordings of brain activity, the
278 emerging results suggest that the recognition of compounds is achieved at distinct stages that are governed
279 by semantics. We showed that the course of activation varies in terms of word complexity and semantic
280 transparency.

DISCLOSURE/CONFLICT-OF-INTEREST STATEMENT

281 The authors declare that the research was conducted in the absence of any commercial or financial
282 relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

283 Authors Teon L. Brooks and Daniela Cid de Garcia share first-authorship as they have both equally
284 contributed to the paper.

ACKNOWLEDGEMENT

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FIGURES
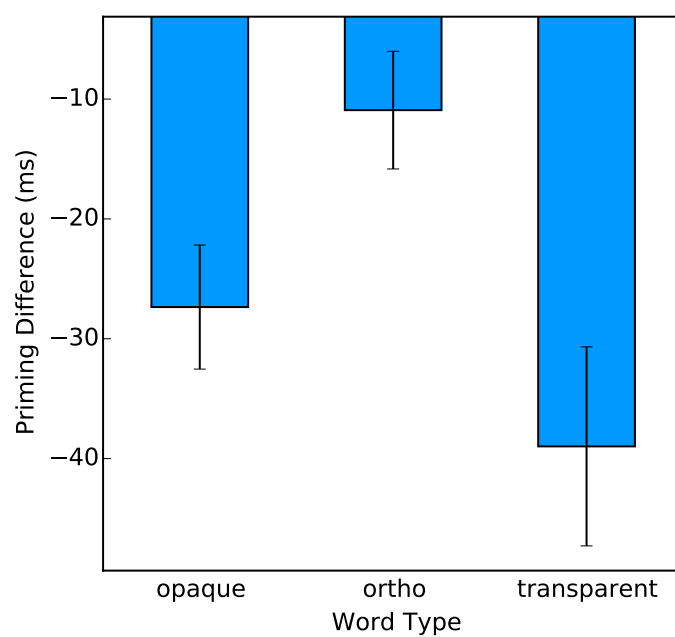
Figure 1. Constituent Priming Differences in Latency Times
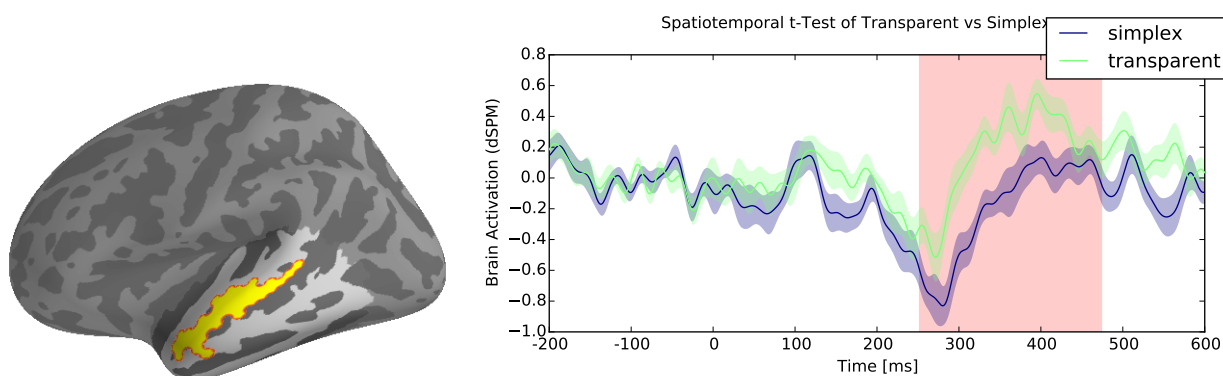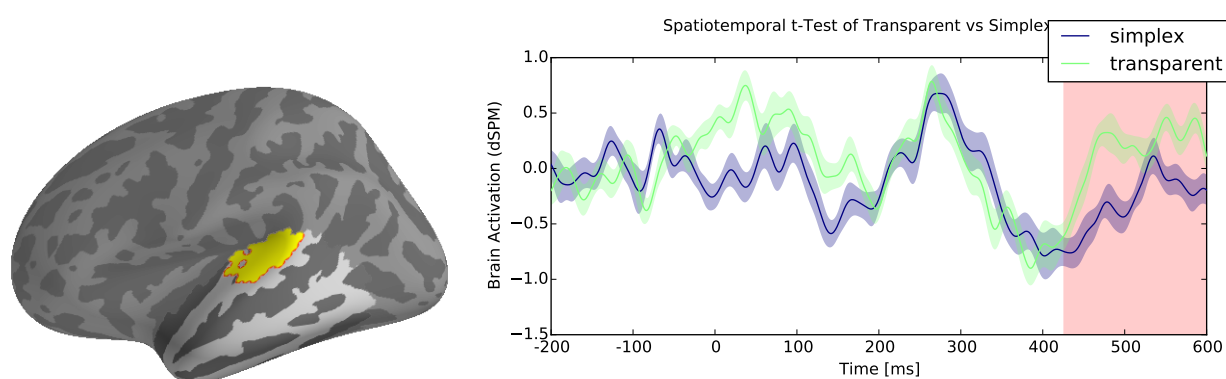

Figure 2. Transparent vs Simplex Difference in LATL

Figure 3. Transparent vs Simplex Difference in posterior Temporal Lobe