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Decompositional representation of morphological complexity: Multivariate fMRI evidence from Italian.

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Abstract

Derivational morphology is a cross-linguistically dominant mechanism for word formation, combining existing words with derivational affixes to create new word-forms. However, the neurocognitive mechanisms underlying the representation and processing of such forms remains unclear. Recent cross-linguistic neuroimaging research suggests that derived words are stored and accessed as whole forms, without engaging the left-hemisphere perisylvian network associated with combinatorial processing of syntactically and inflectionally complex forms. Using fMRI with a 'simple listening' no-task procedure, we re-examine these suggestions in the context of the root-based combinatorially rich Italian lexicon, to clarify the role of semantic transparency (between the derived form and its stem) and affix productivity in determining whether derived forms are decompositionally represented and which neural systems are involved. Combined univariate and multivariate analyses reveal a key role for semantic transparency, modulated by affix productivity. Opaque forms show strong cohort competition effects, especially for words with nonproductive suffixes (*ventura*, 'destiny'). The bilateral fronto-temporal activity associated with these effects indicates that opaque derived words are processed as whole forms in the bihemispheric language system. Semantically transparent words with productive affixes (*libreria*, 'bookshop') showed no effects of lexical competition, suggesting morphologically structured co-representation of these derived forms and their stems, while transparent forms with nonproductive affixes (*pineta*, pine forest) show intermediate effects. Further multivariate analyses of the transparent derived forms revealed affix productivity effects selectively involving left inferior frontal regions, suggesting that the combinatorial and decompositional processes triggered by such forms can vary significantly across languages.

Introduction

Derivational morphology is a cross-linguistically dominant strategy for creating new words (or lexemes) through the combination of existing words and morphemes with a derivational affix (e.g., *happy* + *-ness* -> *happiness*). However, the neurocognitive mechanisms underlying the representation and processing of such derived forms are still unclear. Psycholinguistic theories of morphological processing propose diverging hypotheses on how such forms are represented in the mental lexicon, ranging from strong full-listing models (e.g., Butterworth, 1983) to fully decompositional accounts (e.g., Taft, 2004). These are difficult to reconcile within a coherent interpretive framework, as well as with the very diverse neuropsychological and neuroimaging literature on derivational processing in different languages (e.g., Badecker & Caramazza, 1991; Marangolo et al., 2003; Meinzer et al., 2009; Leminen et al., 2011). This has motivated a systematic cross-linguistic exploration of the processing of derivational morphology in its neurobiological context (for review see Marslen-Wilson, Bozic and Tyler, 2014), aimed at uncovering the neurocognitive properties of derivationally complex forms.

Bihemispheric framework for spoken language comprehension

This research assumes that spoken language comprehension relies on interdependent but functionally dissociable neurobiological substrates: a bihemispheric system, underlying general perceptual and semantic/pragmatic interpretation of auditory input, and a left hemisphere (LH) fronto-temporal system, linking left inferior frontal gyrus (LIFG) with posterior temporal regions, that is selectively involved in the decompositional analysis of morphosyntactically complex sequences, including inflected words (Bozic et al., 2010; Marslen-Wilson & Tyler, 2007; Marslen-Wilson et al., 2014). A series of cross-linguistic fMRI studies in English, Polish and Russian focused on the patterns of neural activation associated with derivationally complex forms, with the consistent finding that derived words like English *bravely* or Polish *czytanie*, ‘reading’ (from *czytac´*, ‘to read’) robustly engaged the bilaterally distributed fronto-temporal system, previously shown to support the perceptual/cognitive interpretation of simple monomorphemic words (Bozic et al., 2010), but did not selectively activate the left-lateralized fronto-temporal system (Bozic et al., 2013a; 2013b). This selective LH activation seems to be a hallmark of decompositional and combinatorial linguistic processing. In a further, more direct contrast between complex derived forms in Russian and matched inflectionally and syntactically complex forms, the derived forms activated only bilateral temporal regions, while inflectional and syntactic complexity in addition strongly activated LIFG (Klimovich-Smith, Bozic, & Marslen-Wilson, 2013). These results, apparently challenging both strong and weak decompositional accounts of morphological processing (e.g., Marslen-Wilson, Tyler, Wachsler & Older, 1994; Taft, 2004), suggested that, unlike inflections, derived words are stored as whole-word form representations and that they are not accessed decompositionally *via* their constituent stem and affix morphemes.

This, however, cannot be the full story, since activation within the bihemispheric system is modulated by the perceptual and linguistic complexity of derived words. Earlier research with morphemically simple forms with onset embedded competitor words (e.g., *clamp* with onset embedded *clam*) shows bilaterally distributed increases in activation as a function of the relative frequency of the whole form and the onset-embedded competitor (e.g., Bozic et al., 2010; Szlachta et al., 2012). The higher the relative frequency of the competitor, the stronger the increase in activation. This cohort competition effect (Marslen-Wilson, 1987), which is assumed to reflect competition between two (or more) simultaneously active word candidates, is also seen cross-linguistically for a variety of derived and pseudo-derived forms. In English (Bozic et al., 2013a), apparent competition effects are seen not only for semantically opaque stems with either productive or non-productive suffixes (e.g., *archer*, *breadth*) but also for transparent stems combined with a non-productive suffix (e.g., *warmth*). Similar bilateral temporal competition effects are also seen in Polish (Bozic et al., 2013b; Szlachta et al., 2012), both for derivationally simple words with an onset-embedded pseudostem (e.g., *kotlet*/*kot*, ‘cutlet’/’cat’) and for opaque suffixed forms (e.g., *sekretarz/sekret*, ‘secretary’/’secret’). These competition effects, sensitive to the relative frequencies of the whole form and of the onset embedded competitor, are consistent with the view that derived and pseudo-derived words are accessed non-decompositionally as stored whole forms, in the same way as morphologically simple words.

It is striking, therefore, that no competition effects are seen, either in English or Polish, for transparent derived forms with productive affixes. In the English data (Bozic et al., 2013a), transparent productive forms (e.g., *bravely*) patterned with simple monomorphemic words that have no onset-embedded competitor (e.g., *giraffe*), suggesting that the onset-embedded stems of these forms (e.g., *brave*), unlike the embedded stems of words like *warmth* and *archer,* were not functioning perceptually as cohort competitors with the whole form. The same outcome is seen for Polish (Bozic et al., 2013b), where a direct comparison between transparent forms (e.g., *czytanie*, ‘reading’) and opaque forms (e.g., *sekretarz*, ‘secretary’), where the two stimulus sets were matched for level of competition between embedded stem and whole form, showed robust competition effects in bilateral temporal cortex for the opaque items, but no effects for the transparent items (all of which had productive affixes).

These results are inconsistent with a uniform whole-form account for derivational morphology in the languages tested. The finding that an onset-embedded stem like *brave* does not generate cohort competition with its whole form *bravely* seems to require some degree of morphological parsing and decompositional representation for transparent derived forms with productive affixes. This is consistent with earlier theoretical claims (e.g., Clahsen et al., 2003; Marslen-Wilson, 2007) and with behavioural research (in both English and Polish) contrasting transparent and opaque derived forms in cross-modal priming paradigms. Studies in English (e.g., Marslen-Wilson et al., 1994) show significant priming between semantically transparent derived forms and their stems (*happiness/happy*) but not for synchronically opaque pairs (e.g., *witness/wit*). Identical results are seen for Polish (Reid & Marslen-Wilson, 2003), contrasting transparent pairs like *szycie/szyć* ‘sewing/to sew’ with opaque pairs such as *jałowiec/jałowy* ‘a juniper/poor, futile’.

These results, together with the direct neuroimaging evidence that onset-embedded transparent stems do not function as cohort competitors, point to underlying differences in the lexical representation of transparent as opposed to opaque forms, coupled with decompositional processing during lexical access. The absence of cohort competition is consistent, in fact, with the type of decompositional account proposed by Marslen-Wilson et al. (1994), where the same morphemic representation (e.g., *happy*) functions both as an independent lexeme, and as a combinatorial component of associated transparent derived forms (e.g., *happily*, *happiness, unhappy*). These inferences, however, do not sit well with the repeated failure to see any selective activation of the LH fronto-temporal system. This system, as noted above, is critically involved in the language-specific decompositional and combinatorial processes that support inflectional morphology and hierarchical syntax. There seems no *a priori* reason why such a system should not also support the application of these processing functions to derivationally complex forms with the appropriate synchronic properties of semantic transparency and affix productivity. Indeed, the Bozic et al. (2013a) study was conducted on just this assumption, where forms like *bravely* and *happiness* were expected to behave, neuro-cognitively, in the same way as regular inflectional forms. The absence of selective LH activation, for both Polish and English transparent forms, suggests either that these forms are not in fact combinatorially processed, or that such processes can also be supported by bihemispheric, potentially more domain-general systems, consistent with recent claims for aspects of syntactic processing (Bozic et al., 2015).

In the fMRI study reported here we seek to move these issues forward by examining them (a) in a language (Italian) with a much richer, and potentially more combinatorial derivational word-formation system than English, where (b) well-developed computational lexicographic resources are available for determining the relevant distributional properties of the language along the dimensions of affix (and stem) productivity[1], and (c) by employing both univariate analysis techniques, primarily sensitive to average differences in overall neural activation level between conditions, and multivariate pattern analysis techniques (Kriesgeskorte et al. 2008; Nili et al., 2014) that are potentially more sensitive to the qualitative properties of neural computations elicited by different linguistic inputs. In this context, and using the presence or absence of cohort-competition effects as an index of underlying decompositional representation, we aim to clarify under what conditions, and in which brain regions, derivationally complex forms are represented either morphemically or as unanalyzed whole forms.

Transparency, productivity and competition in Italian derivational morphology

Italian is a Romance language with a root-based morphology in which derivational and inflectional suffixes specify different types of morpho-semantic and morpho-syntactic information. A semantically transparent derived word like *libreria*, ‘bookshop’, for example, can be decomposed into the stem morpheme *libr(o)*, “book”, the productive derivational suffix *-eri-*

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[1] Such resources were not readily available for the Bozic et al. (2013b) study in Polish – hence the absence of an affix productivity contrast in that experiment.

(with a locative meaning usually linked to a commercial activity), plus the inflectional ending *-a*, which marks both the feminine gender and the singular number. These processes are ubiquitous in Italian. About 30% of the basic Italian vocabulary and more than 50% of the lexical entries coined in the 20th century (Iacobini, 2010), are derived by word formation processes involving more than 180 derivational suffixes (Grossmann and Rainer, 2004), generating nouns, adjectives, verbs and adverbs.

These derived constructions are part of a diachronically stratified lexicon and can often be traced back to the Latin origins of modern Italian, showing how a word formation mechanism evolved and became active or lost, producing semantically transparent and opaque words combined with productive and non-productive affixes. For instance, in the opaque form *ventura*, ‘destiny’, the non-productive suffix *–ura* is appended to the embedded stem *vent*-, which is etymologically related to the form and meaning of "vent-urus", the future participle of the Latin verb *venio, -ire*, “to come”, which no longer exists in Italian. Synchronically the apparent embedded stem form is *vento*, "wind", which is not semantically related to the meaning of the word. These properties of Italian derivational morphology make it possible for derived words in Italian to be systematically contrasted in terms of both their semantic transparency and their affix productivity, giving rise to a gradient of derivational complexity (c.f., Bozic et al., 2013a). We constructed highly controlled sets of stimulus words across four principal experimental conditions, overlapping with previous studies in English and Polish, in order to provide a robust test, in a new cross-linguistic environment, of the determinants of decompositional or whole-form representation of derived words.

As in previous neuro-imaging and behavioural studies, the primary dimension is the synchronic semantic relatedness - as assessed by native speakers’ rating judgments - of the relationship between the meaning of the onset-embedded derivational base morpheme and the meaning of the derived full form, ranging from highly transparent forms like *bravely* or *happiness* to opaque forms like *archer* or *breadth*. The English and Polish fMRI studies consistently show increased activation and significant cohort competition effects for semantically opaque words, indicating that these forms and their onset-embedded stems or pseudo-stems are separately represented lexemes. The competition effects elicited by these forms activate bilateral brain regions, primarily in the middle temporal lobes. For semantically transparent forms, however, there is some indication that the presence or absence of cohort competition is modulated by the productivity of the derivational affixes involved, where productivity is a measure of whether a derivational suffix is currently in use to create new words in the language.

As noted above, Bozic et al. (2013a) found that highly transparent derived forms with unproductive affixes, such as *warmth* (with the unproductive affix –th), nonetheless seemed to pattern with the semantically opaque forms (such as *archer*), showing comparable increases in levels of neural activation relative to baseline. Consistent with earlier behavioural research (e.g., Marslen-Wilson et al., 1996; Ford, Davis & Marslen-Wilson, 2010) this suggests that complex words with unproductive suffixes, even if semantically transparent, are less likely to be stored and processed decompositionally. On the other hand, in the multivariate analyses conducted in the same Bozic et al. (2013a) study, no effects of productivity *per se* were seen, either as a main effect or in interaction with semantic relatedness and lexical competition. It is in any case unclear how generalizable these productivity effects might be cross-linguistically. The parallel Polish study (Bozic et al., 2013b), for example, did not contrast stimuli along this dimension, and only productive suffixes were used.

In the current study, therefore, transparency and productivity are fully crossed, giving a two-way set of contrasts similar to those tested in the original English study (Bozic et al., 2013a). A first group of words consisted of semantically transparent forms with an intact synchronic link with the meaning of their derivational bases (as reflected in native speaker relatedness ratings) and using derivational suffixes productively employed in current Italian - as in the example *libr-eria* given above, with the embedded stem *libro*. The second group consisted of similarly rated semantically transparent words such as *pin-eta*, “pine forest”, with the embedded stem *pino*, ‘pine tree’, but combined with the non-productive suffix‘*-eta*’. These are comparable to the *warmth* set in English (Bozic et al, 2013a). Two corresponding sets of semantically opaque words were also formed with either productive or unproductive suffixes. Thus the form *tomb-ino,* ‘manhole’, with the semantically unrelated embedded stem *tomba*, ‘tomb’, is combined with the productive diminutive suffix ‘-ino’ to form the third group of stimuli, while the fourth group consisted of equally opaque forms like *prem-ura,* ‘urgency’, with the opaque embedded stem *prem-(ere)*, ‘to push’ combined with the unproductive affix ‘*-ura*’. These derivationally complex items were contrasted with a baseline condition containing simple words with no derivational internal structure (e.g., *albero*, “tree”) and no onset-embedded stem.

For each of the four complex word sets, potential lexical competition is held constant, measured in terms of the frequency divergence between the embedded stem or pseudo-stem and the whole form. The higher the frequency of the stem relative to the whole form, the stronger should be the competition effect. In the Polish data (Bozic et al., 2013b) we saw a striking disjunction between transparent and opaque sets, with no lexical competition effects for the transparent items. We ask here whether this distinction also holds for Italian, with a similar root-based morphology to Polish, and whether these effects are modulated by affix productivity, with some indication from English (Bozic et al., 2013a) that transparent forms with unproductive affixes are not decompositionally represented, so that competition effects should still be present. Finally, by using potentially more sensitive multivariate pattern analysis methods (Kriegeskorte et al., 2008; Nili et al., 2014), we will revisit the issue of whether selective left fronto-temporal involvement can be detected for the maximally decomposable transparent productive conditions.

2. Methods

2.1 Participants

Twenty healthy volunteers participated in the study. All participants were right-handed Italian native speakers with no history of developmental, neurological or psychiatric disorders. They had normal or corrected-to-normal vision. All participants gave their informed consent to take part in the study and were remunerated for their time. Ethical approval was obtained from the Cambridge Psychology Research Ethics Committee.

2.2 Materials and Design

Stimuli. The experiment included 5 conditions with 80 words each (See Table 1). The analytical dimensions affecting morphological analysis and decomposability were co-varied in conditions 1-4, which included 1) semantically transparent words with productive suffixes (*libr-eria*, "bookshop”), 2) semantically transparent words with unproductive suffixes (*pin-eta*, "pine forest"), 3) semantically opaque words with productive suffixes (*tomb-ino*, "manhole"), and 4) semantically opaque words with unproductive suffixes (*prem-ura*, "urgency"). Condition 5 consisted of morphologically simple words (e.g., *albero*, ‘tree’) with no derivational structure.

----- Table 1 about here ----

All words were extracted from the WaCky Wide Web Corpus (Baroni et al., 2009), consisting of more than 1.5 billion word tokens and 3.6 million word types, providing a wide synchronic sample of current Italian. The test words were selected from an initial list of 800 morphologically complex words by applying a series of selection criteria. These included behavioural evaluation, corpus-based quantitative assessment and qualitative grammatical/lexicographic validation with respect to three parameters: semantic transparency, suffix productivity and lexical competition.

Semantic Transparency: An online rating study was conducted to assess the degree of semantic transparency of each experimental item, defined as the extent to which the meaning of the derived word was synchronically linked to the meaning of its embedded derivational base (e.g., *cambiamento*/*cambiare*, "change/to change", vs. *inventario*/*inventare*, "inventory/to invent"). 100 native Italian speakers took part in the study. They judged whether the meaning of each of the 800 complex words was related to the meaning of its embedded stem, using a 5 point scale. Complex words with ratings of 4 to 5 for 75% of the participants were assigned to the transparent conditions. The opaque conditions were restricted to words with ratings of 1 to 3 for 75% of the participants. The within-condition variation in rating scores was used to explore the specific effects of semantic relatedness for the different groups.

Suffix Productivity: This was defined as the probability p that a suffix is used to create new words and measured as $p = h/N$, where h is the number of *hapax legomena* (words with a given suffix that is attested only once in the corpus) and N is the total number of tokens for that affix (Baayen and Lieber, 1991). The average ratios for the four suffixed conditions are given in Table 1. This corpus-based approach to suffix productivity assumes that if a complex word occurs only once in a corpus it is likely to be a new lexical entry resulting from a new combination of a stem and a suffix. As an additional check on whether a suffix was synchronically productive, we also determined whether it had been used to generate new words in the last 10 years. All the words classified as productive had suffixes that met this criterion.

Lexical Competition: This was defined as the ratio between the logarithmic frequencies of the onset-embedded stem or pseudo-stem and of the lemma of the derived form, as quantified by a corpus-based analysis. These measures were preferred to the simple stem form measure used in our earlier work on English (Bozic et al., 2010), because they better reflect the root-based morphological properties of the Italian lexicon, where inflectional grammatical morphemes mark the number and gender of nouns and adjectives and the person and tense/mood of the verbs. Thus, for a form like *guidatore*, 'driver' with the stem *guid-* (from the verb *guidare, 'to drive'*), the frequency of the verbal stem includes all of its inflectional and derivational suffixed variants (e.g.: guidare, guidando, guida, guidava, guidatrice, guidatori), as attested in a large Italian corpus (Baroni et al., 2009), and the lemma of the derived form includes its inflectional forms (e.g. guidatore, guidatori). These competition ratios were held constant across the four derivational conditions.

These variables define a potential complexity gradient across the four primary experimental conditions, which co-vary morpho-semantic transparency and productivity, while matching degree of lexical competition across these conditions (see Table 1). A fifth condition consisted of simple words with no derivational structure (e.g. *albero* "tree").

The conditions (in order 1-5) were matched on average number of phonemes (3.85, 3.82, 3.83, 3.85, 3.75), acoustic duration in seconds(1.2, 1.2, 1.2, 1.2, 1.1), log whole-word frequency (3.52, 3.47, 3.56, 3.60, 3.38) and log lemma frequency (3.86, 3.65, 3.85, 3.88, 3.74). Each condition contained words (almost all nouns) derived from either verbs (deverbal) or nouns (denominal).

The 400 test words were interspersed with 100 filler words, 200 acoustic baseline trials and 200 null event trials (silence). The baseline was envelope-shaped, length-matched "Musical

Rain" (MuR), sharing the auditory properties of the spoken words, without inducing phonetic interpretation. The baseline was created by extracting the temporal energy envelope from each spoken word and then filling these with jittered fragments of synthesized speech (Uppenkamp et al., 2006). The MuR stimuli so obtained are matched in RMS levels and spectro-temporal energy distribution to the spoken stimuli, but do not trigger a speech percept (Bozic et al., 2010).

2.3 Experimental Procedure

We adopted a ‘natural’ listening task with an occasional 1-back memory task, intended to keep the participants awake and attentive. For 5% of trials, a question appeared on the screen asking whether the meaning of the word they were hearing was the same as the previous one. Participants pressed a left button (same=YES) and a right button (different=NO) with their left hand. There were a total of 900 trials, pseudo-randomised across 4 blocks.

2.4 Imaging Methods

Scanning was performed on a Siemens 3T Tim Trio Scanner, using a fast sparse imaging protocol. Each trial consisted of a 1.4 sec silence and 2 sec acquisition, with sounds played within the silent periods to minimize interference of scanner noise with auditory processing. Gradient-echo imaging (EPI) sequence parameters were TR = 3.4 sec, TA = 2 sec, echo time = 30 msec, flip angle = 78 degrees, matrix size = 64x64). The functional images consisted of 32 slices covering the whole brain (slice thickness 3mm, in-plane resolution 3 x 3mm, inter-slice distance 0.75mm). MPRAGE T1-weighted scans were acquired for anatomical localisation.

2.5 Data Analysis

Preprocessing. Imaging data were analysed using SPM8 software (Wellcome Department of Imaging Neuroscience, London, UK). For both univariate and multivariate analyses, images were corrected for slice timing and spatially re-aligned to the first image using sinc interpolation.

The EPI images were co-registered to the structural T1 images using standard coregistration procedures. The structural MRI was normalised to the 152-subject T1 template of the Montreal Neurological Institute (MNI). The resulting transformation parameters were applied to the co-registered EPI images. During the spatial normalization, images were resampled with a spatial resolution of 2 x 2 x 2mm^3.

2.6 Univariate analysis

For the univariate analysis, normalised images were spatially smoothed by convolution of a 10-mm full-width half-maximum Gaussian kernel and globally normalized. Single subject statistical comparisons were computed by using the general linear model (Friston et al., 1998). Low-frequency noise was removed by applying a high-pass filter of 128 sec. The neural response for each event type was modelled with the canonical haemodynamic response function (HRF). Motion regressors were included as covariates of no interest to account for any residual movement effects. Group data were analysed using random effects analysis. Further we examined the realignment parameters for all participants to ensure head motion was not in excess of 4 mm in any direction during the test sessions. Whole brain analysis results are displayed after controlling for false discovery rate (FDR) at 0.05 for multiple comparisons at cluster level. Stereotaxic coordinates for voxels with maximal t-values within activation clusters are reported in the Montreal Neurological Institute (MNI) standard space.

Consistent with our predictions and previous work (Bozic et al., 2010; Tyler & Marslen-Wilson, 2008; Binder et al., 1997), a bilateral fronto-temporal volume of interest was selected for both univariate and multivariate analyses. Using PickAtlas, a mask was created, including bilateral temporal lobes (superior, middle and inferior temporal gyri, including temporal poles), angular gyrus), inferior frontal gyrus (pars opercularis - BA44, pars triangularis - BA45, pars orbitalis– BA47) and the anterior cingulate. All results were assessed and displayed using this mask.

2.7 Multivariate Analysis

For multivariate RSA, the analysis was carried out in subject native space, using realigned, unsmoothed and unnormalised functional data, which were co-registered with the MPRAGE of each subject. Data were analyzed using the general linear model to create parameter estimates for each item, which were used to compute *t*-statistic maps. Data were then extracted for each participant individually using a "sphere of information" searchlight approach (Kriegeskorte et al., 2008; Nili et al., 2014). A roaming spherical searchlight with 5mm radius (Kriegeskorte et al., 2008) was moved throughout the grey matter to extract continuous, voxel-by-voxel maps of word-elicited activation values. To achieve maximal sensitivity to our experimental manipulations, this analysis was based on single items, with each experimental word modeled as a condition and associated with a separate hemodynamic predictor. The correlation distances (1-Pearson's correlation) between the response patterns for each word paired with every other word were expressed as representational dissimilarity matrices (RDMs), which are symmetric about a diagonal of zeros (Kriegeskorte et al., 2008). These brain data RDMs were then correlated with theoretical model RDMs (using Spearman's rank correlation) at each brain location. The resulting maps of r values for each participant and model were normalised onto the MNI template and entered into a group-level random-effects (RFX) analysis using permutation-based non-parametric statistics in SNPM (http://www2.warwick.ac.uk/fac/sci/statistics/staff/academic-research/nichols/software/snpm), to test for positive correlations between the model RDMs and brain data RDMs. FDR correction at

0.05 for multiple comparisons across voxels and number of models was applied. 10,000 permutations were used in the analysis.

3. Results

3.1 Univariate Analyses

To assess the regions involved in general lexical processing, we contrasted all words against the MuR baseline (see Table 2). This comparison showed activations in bilateral middle and superior temporal gyri (MTG, STG), extending to LIFG (BA 44-45-47), and RIFG (BA 45-47), broadly consistent with the previous literature (e.g., Bozic et al., 2010; 2013; Binder et al., 1997).

---- Table 2 about here ----

We then examined lexical processes specific to individual experimental conditions, contrasting each condition against MuR separately. Relative to baseline, transparent productive words engaged bilateral temporal regions (Figure 1a, Table 3a), with no sign of selective LIFG activation, consistent with previous univariate results for English and Polish (Bozic et al., 2013a; 2013b). Transparent non-productive words activated bilateral temporal regions and LIFG BA 47 (Figure 1b, Table 3b). This region of LIFG is generally not associated with combinatorial morphosyntax. Opaque productive words activated bilateral MTG, with activation extending to right STG, left superior temporal pole, and LIFG BA 44-45 (Figure 1c, Table 3c). Opaque non-productive words activated large extents of bilateral temporal and inferior frontal regions (BA 44-45-47) (Figure 1d, Table 3d). Derivationally simple words activated the fronto-temporal system bilaterally (Figure 1e, Table 3e), but with substantially stronger activation of LIFG (BA 44, 45, 47) than of RIFG (BA 44).

---- Figure 1 and Table 3 about here ----

We then turned to a more global set of comparisons, designed to pull out the effects of the major dimensions of transparency and productivity as they varied across the four factorial conditions (1-4). These show that the dominant univariate activation effects are for the opaque items, most strongly for the opaque non-productive condition, and with no evidence for selective LIFG engagement. First, we compared all opaque words with all transparent words, collapsing across productivity. Here we see (Figure 2a, Table 4a) stronger bilateral fronto-temporal activation for opaque words overall, with similar levels bilaterally of STG and MTG activation, and smaller bilateral effects in BA44 and 45. We then unpacked these results to explore the effects of transparency and opacity on responses to non-productive and productive words separately. No significant differences were seen for the contrast between opaque and transparent productive words. Opaque non-productive words, however, elicited much stronger activation than transparent non-productive words (Figure 2b, Table 4b), with strong bilaterally balanced effects in L and R STG, MTG, BA 44 and precentral gyrus.

---- Figure 2 and Table 4 about here ----

Comparisons between non-productive and productive forms (collapsing across transparency) showed no activation differences. Breaking down these results for transparent and opaque words separately, we found no differences between transparent non-productive and productive words. Opaque non-productive forms, in contrast, exhibited increased activation compared to opaque productive forms in temporal cortex bilaterally, with smaller effects in R BA47 and BA45 (Figure 2c, Table 4c).

In a final univariate examination of the key dimensions manipulated in this study - semantic transparency and suffix productivity in relation to cohort-based lexical competition – we ran a series of correlational parametric modulator analyses, conducted at the individual item rather than condition level, and separately for the opaque and for the transparent word sets. For these analyses, main effects of the three modulator variables (transparency, productivity, and competition ratio) were only seen for the opaque words (as plotted in Figure 3). We focus on the results for these opaque sets first.

---- Figure 3 about here ----

For lexical competition, defined as the ratio between the log frequencies of the suffixed morphological variants of the embedded stem or pseudostem and the log lemma frequency of the whole form, increased competition (i.e. higher relative frequency for the embedded stem) led to increased activation in MTG (BA 21) bilaterally for the opaque forms, although the LH effects were only marginally significant (cluster level uncorr $p<0.01$). This is consistent with the results seen for Polish (Bozic et al., 2013b), where lexical competition effects were also only significant for the opaque items. Effects were similar for semantic relatedness, with bilateral activation in MTG (BA 21), which again was only marginally significant in the LH. These effects broadly overlap with the lexical competitor effects in bilateral MTG. The third variable, of suffix productivity, showed marginally significant ($p<0.01$) increases in activation associated with decreased productivity. These effects, where lower suffix productivity is associated with higher levels of neural activation, were seen in bilateral inferior frontal regions (left insula, left BA 44 and BA 47, right BA 45) and in the left inferior temporal gyrus.

The trends seen in these parametric modulator results are consistent with the preceding subtractive analyses in suggesting that semantic transparency is the primary variable determining the representational and processing relationship between derivationally complex forms and their onset-embedded stems (or pseudo-stems). Only the opaque forms show significant across-the-board effects of lexical competition, consistent with the view that the increased activation for these forms reflects cohort competition between the separate lexical representations for the derived forms and for their embedded stems or pseudostems. This competition between cohort members (e.g, between *ventura* and *vento*) is amplified by the presence of a non-productive suffix and by decreased semantic relatedness between the whole form and its onset-embedded competitor.

Turning to the transparent items, these show no overall effects for the main modulator variables. Differences only start to emerge when we break down the transparent sets according to productivity. For the transparent productive words, such as *libreria* or *guidatore*, there is still no evidence for competition effects, similar to previous results for English and Polish (Bozic et al, 2013a; 2013b). The transparent nonproductive words (such as *pineta*), in contrast, diverge from the results for the productive words, consistent with the univariate English results for forms like *warmth*. Bilateral temporal effects are seen both for semantic relatedness and for lexical competition, although in the opposite direction to results for the opaque items. Increased semantic relatedness is linked to increased activation in left STG and right MTG, while decreased lexical competition is linked to increased activation in left ITG and right MTG. This suggests that these effects are not driven by cohort competition in the same way as for the opaque items. We return to these contrasts in the Discussion section below.

3.2 Multivariate Analyses

Representational Similarity Analysis is a multivariate pattern analysis technique that can directly test theoretical claims about the nature and content of neural computations, sampled on a brain-wide basis using a ‘searchlight’ procedure (Kriegeskorte, 2008; Nili et al., 2014). To do this requires the development of model Representational Dissimilarity Matrices (RDMs) to represent hypotheses about the role of different morpholexical variables in the brain's response to the experimental words (see Figure 4). To increase the power and sensitivity of these analyses, we constructed the model RDMs, and the corresponding data RDMs, on a ‘single trial’ basis, where each item is entered individually into the dissimilarity matrix, rather than examining effects at a condition level averaging across items.

The first set of model RDMs (Figure 4A) tested for patterns of activation related to cohort-based perceptual competition, defined as the ratio between the log frequencies of the embedded stem lemma and the whole form lemma. The All Words Lexical Competition RDM expresses the pairwise relationship of these values for every word in Conditions 1-4 of the experiment. This gives a 320 x 320 data matrix (Figure 4A.1). This reduces to two smaller matrices, each 160 x 160 cells, for the transparent words alone (Fig 4A.2) and for the opaque words alone (Fig 4A.3).

----- Insert Figure 4 about here -----

The results (see Fig 5A and Table 5A) for the All Words set show significant model fit in bilateral STG and MTG, in R and L Cingulate, and with relatively weak bilateral IFG effects. Breaking the data down into Opaque and Transparent subsets, no Lexical Competition effects were seen for the Transparent words, while effects for the Opaque forms (Table 5B and Figure 5B) were seen in bilateral STG. In further analyses, partitioning the data according to productivity, no significant model fit was seen.

----- Insert Figure 5 and Table 5 about here -----

A second set of model RDMs (Fig 4B) tested for effects of semantic relatedness between the derived words and their embedded stems, based on native speakers’ judgments about the link between their meanings. The resulting 320 x 320 All Words model RDM (Fig 4B.1) shows bilateral temporal and inferior frontal fit, as well as large clusters in R and L fusiform (Fig 6A and Table 6A). In sub-analyses conducted on the Transparent and the Opaque model RDMs separately (Fig 4B.2 and 4B.3), no effects were seen for variations in semantic relatedness within the set of Transparent words, similarly to the Lexical Competition results. There were strong effects for the Opaque words (Fig 6B and Table 6B), with these being substantially larger in Opaque Productive words (Fig 6C and Table 6C) than in Opaque Non-Productive words (Fig 6D and Table 6D).

----- Insert Figure 6 and Table 6 about here -----

The final set of model RDMs (Fig 4C) tested for effects of suffix productivity, quantified (as described earlier) in terms of the Baayen & Lieber (1991) *hapax legomena*-based procedure. Again, we constructed an All Words 320 x 320 model RDM (Fig. 4C.1), and two 160 x 160 submatrices for Transparent and Opaque Words separately (Figs 4C.2 and 4C.3). In contrast to the results for the Lexical Competition and Semantic Relatedness analyses, we saw no significant model fit for the All Words model RDM, nor for the Opaque Words sub-matrix. Instead we see significant results for the Transparent Words model RDM (Fig 7A and Table 7A), with strong bilateral temporal effects in STG (BA 21), extending into MTG and Temporal Pole in the RH, and with significant model fit in LIFG (BA 44) but not in RIFG. This is the first evidence we have seen for selective engagement of the left perisylvian language system by derived forms. A further breakdown of the Transparency model RDM into two 80 x 80 Productive and Non-Productive matrices revealed no effects for non-productive words and reduced effects for transparent productive words, restricted to temporal regions bilaterally (Fig 7B and Table 7B).

---- Insert Figure 7 and Table 7 about here ----

4. Discussion

In the context of the incomplete but intriguing results from previous cross-linguistic neuroimaging studies, this research used a combination of univariate and multivariate methods to probe the respective roles of semantic transparency and affix productivity in determining whether derivationally complex word-forms are decompositionally represented, and to establish which brain regions are primarily involved in the perceptual interpretation of these forms.

The primary finding is a defining role for semantic transparency – though significantly modulated by affix productivity – in determining the underlying representation of derivationally complex forms,. The opaque and transparent sets, separated on the basis of their judged semantic relatedness, interacted differently with the variables of competition, semantic relatedness, and productivity. This generated three main classes of effects, which are discussed in the following sections.

Opaque forms

For the opaque forms (e.g., *ventura*, 'destiny'), the results consistently indicate that these are represented as 'whole forms', defined as a separate lexical entry (or lexeme) with no internal representation of morphemic structure, such that the onset-embedded unrelated stem or pseudostem constitutes a second, different lexeme (e.g., *vento*, 'wind'). This second lexeme acts as a strong cohort competitor, potentially delaying the recognition of the derived form, in a manner similar to the cohort competition effects seen for morphologically simple forms with onset-embedded competitors (e.g., *ram*/*ramp*) (Bozic et al., 2010; Szlachta et al., 2012). The higher the frequency of the onset-embedded stem or pseudostem, the stronger a competitor it will be for the derived form that the participant is actually hearing. In the univariate analyses (Figure 3), increases in activity associated with increased levels of lexical competition are only seen for the opaque conditions. Consistent with this, in the RSA analyses only the lexical competition model specific to the opaque words fits the patterns of brain activity (Fig 5, Table 5).

The uniformly bilateral distribution of these competition effects, and the absence of selective left perisylvian activation, indicate that the processing domain for the perceptual analysis of the opaque forms is the domain-general bihemispheric system (Bozic et al., 2010; Marslen-Wilson et al., 2014). The RSA results, furthermore, show model fit in bilateral dorsal IFG (BA 44-45) - associated with the selection between automatically retrieved competitors (Thompson-Schill et al., 1999; Zhuang et al., 2014) – as well as in anterior cingulate cortex (Botvinick et al., 2004) and middle/posterior temporal regions (Bokde et al., 2001). Activity in all these regions has been found in association with increases in lexical competition (e.g., Bozic et. al., 2010; 2013).

The conclusion that the processing activity elicited by the opaque items is primarily driven by the perceptual competition between two (or more) active lexical candidates is supported by the results for the semantic relatedness dimension. As noted earlier, relatedness varies not only in terms of the global contrast between opaque and transparent sets, but also within each set separately. In the univariate analyses, the opaque conditions show increased levels of activation in bilateral temporal regions as semantic similarity decreases (Fig 3). The more semantically distinct the embedded stem and the full-form, the stronger the perceptual competition between them. The multivariate analyses give a more differentiated but comparable picture. Again, no model fit is seen for the transparent word data. For the opaque sets, the relatedness RDM fits best in the Opaque Productive subset (Fig 6C), with substantial bilateral fronto-temporal model fit. This encompassed ventral bilateral IFG (BA 47), a key area for semantic processing (Hagoort, 2005) and semantic retrieval (e.g., Wagner et al., 2001), as well as temporal pole and anterior MTG, regions essential for lexical retrieval and language comprehension (e.g., Turken and Dronkers, 2011). Previous findings for English (Bozic et al., 2013) show a bilateral fronto-temporal interaction between semantic relatedness and lexical competition, consistent with the findings here.

The univariate results for the productivity dimension are similarly consistent with a perceptual competition account, with decreased affix productivity leading to increased processing costs. Opaque non-productive forms generate the highest levels of activation overall, relative to the opaque productive forms (Fig. 2C), and the parametric modulator analysis (Fig 3) shows that this increased activation is associated with less productive affixes. The directionality of this effect, and its location in bilateral inferior frontal areas involved in perceptual conflict resolution (Fig 3), suggests that opaque forms with nonproductive affixes generate stronger cohort competition than those with productive affixes. Nonproductive forms like *ventura* are more likely to be treated as nondecomposable simple lexemes in first-pass processing, fully distinct from their onset embedded pseudostems (e.g., *vento*), and therefore processed by the perceptual system in the same way as morphologically simple words with onset-embedded competitors such as *ramp* or *claim*.

These contrasts are likely to be less clearcut for opaque forms like *tombino*, ‘manhole’, where the presence of a highly productive suffix like {-ino} may lead to an initial mis-segmentation as {tomba} + {-ino}, similar to the effects seen in the visual domain for English pseudo-complex words like *corner*, where the presence of the productive affix {-er} leads to a transient misanalysis of the morphologically simple *corner* as {corn} + {-er} (Rastle, Davis, Marslen-Wilson & Tyler, 2000; Whiting, Shtyrov & Marslen-Wilson, 2014). In the current context, these processes would reduce competition effects relative to the opaque non-productive condition, both by slowing the identification of the semantically unrelated opaque form actually present, and by providing potential semantically related alternative readings (i.e., of *tomba* plus a suffix). Note that on this account, the lexical representation of forms like *tombino* is assumed to be morphologically simple and unstructured, similar to lexically simple pseudo-complex forms like *corner* or *brother* in English.

Transparent forms

Focusing first on the transparent forms with productive affixes, these contrast strongly with the opaque forms, showing no sign of competition or relatedness effects in either univariate or multivariate analyses, while revealing significant left-lateralised effects of suffix productivity in the multivariate RSA analyses.

These robust differences between transparent productive words and opaque words point to a view of the representation and processing of transparent productive forms that is strikingly similar to the proposals put forward by Marslen-Wilson et al. (1994) on the basis of purely behavioral priming studies of derivationally complex forms in English. These proposals had two components that are relevant here. The first was that the central representation of derivationally complex forms was determined by their semantic transparency, with only transparent forms (such as *happiness*) being decompositionally represented (as {*happy*} + {-*ness*}), while opaque forms were represented as whole forms (e.g., {*department*}) with no link to their semantically and morphologically unrelated onset-embedded lexemes (e.g., {*depart*}). The second component, required to explain the robust priming between *happiness* and *happy* (but not between *department* and *depart*), was that the same abstract morpheme functioned both as an independent lexeme and as a combinatorial component of the family of derived forms transparently related to this morpheme (e.g., *happiness*, *happily*, *unhappy*, etc).

Functionally equivalent proposals seem required here – in particular, to explain why *libro*, ‘book’, does not function as a cohort competitor to *libreria*, ‘bookshop’. There is little doubt that a form like *libro* is a separate lexeme in the language, which predicts that *libreria* should generate cohort competition in the same way as an opaque form like *ventura* 'manhole', where the synchronically unrelated stem *vento* 'tomb' is activated as a cohort competitor. We see instead that representational overlap (due to semantic transparency) between a derived form and its embedded stem, while driving priming in the behavioral study, seems to neutralise cohort competition in the neural domain.

This decompositional view of the representation and processing of the transparent productive forms may well be linked to the second major divergence between these forms and the opaque sets. This is in the domain of affix productivity, where the RSA analyses reveal significant model fit only for the transparent conditions. These effects implicate the left perisylvian language system, with the characteristic pattern of bilateral temporal involvement accompanied by selective LIFG model fit, primarily in L BA 44. These are brain regions - especially the BA 44/45 and L posterior STG network identified in earlier studies (e.g., Tyler et al., 2005; Marslen-Wilson & Tyler, 2007; Bozic et al., 2015) - with a well-established role in supporting decompositional and combinatorial processing for inflected forms and for syntactically complex phrases and sentences. This suggests that the processing and representation of transparent derivational forms, at least in a root-based word-formation system like Italian (Crepaldi et al., 2014), does share some processing characteristics with inflectionally complex forms, with the derivational affix being separately identified as part of the perceptual access process. Note, however, that this does not imply that Italian derivational affixes participate in phrasal and sentential level morphosyntactic processes in the same way as inflectional affixes. Exactly how they do interface with left perisylvian combinatorial machinery is an issue for further research.

We turn, finally, to the transparent forms with unproductive affixes, such as *pineta*, ‘pine forest’ or *fornaio*, ‘baker’ (combining *forno* ‘oven’ with the unproductive agentive suffix {-aio}). These elicit a third class of effects, intermediate between the results for the productive transparent and the opaque sets, which are consistent with earlier results for English forms such as *warmth*, which indicated that transparent forms with unproductive suffixes are less readily decomposable, despite their semantic relatedness (Bozic et al, 2013a; Ford et al, 2010; Marslen-Wilson et al., 1996). In the current research, the greater lexemic independence of the derived form seems to lead to significant but paradoxical effects of relatedness and competition.

For opaque nonproductive forms, such as *ventura*, it is the dissimilarity between two competing lexemes (*vento* and *ventura*), reflected in decreased semantic relatedness and increased competition ratio, that leads to stronger cohort competition and increased neural activation. For transparent nonproductive forms like *pineta*, in contrast, it is the similarity between potentially competing lexemes (*pino* and *pineta*) that seems to increase activation. As the full form and the onset-embedded stem become more similar, whether in their semantic properties or in their relative frequencies of occurrence, then neural activation increases. This presumably reflects greater difficulty in discriminating the two lexemes involved (cf., Raposo et al, 2006).

These surprising contrasts suggest two things. First, that the strong representational overlap between forms like *pineta* and *pino*, in terms of their rated semantic properties, acts to mitigate cohort competition based on dissimilarity, just as it does for the transparent productive forms. At the same time, however, the apparently greater lexemic differentiation between stem and derived form opens the door for a different type of selection problem, reflecting the degree of similarity between the two forms. The implications of these contrasts, however, for the representational differences between productive and unproductive forms, remains a question for further research.

Conclusions

The results reviewed here for the transparent forms in this experiment – most clearly for those with productive affixes - lead to the conclusion that the same underlying representation, in whatever way it is neuro-computationally realized, participates in the activation of the transparent derived forms and in the activation of their stems. The neuroimaging results are the most direct evidence for this since they do not reflect potential behavioral task demands - as associated, for example, with lexical decision (Wright et al., 2010) – but simply the patterns of neural activation elicited as the listener hears a spoken word. These patterns point to an underlying decompositional and combinatorial substrate for the neural representation of semantically transparent derivationally complex forms. The dynamic neural substrate for a form like *libreria* incorporates the neural substrate for its stem *libro*, reducing cohort competition - and explaining behavioural priming.

This decompositional interpretation is supported by the presence of selective left perisylvian neural activity (Figure 7A), diagnostic of linguistically-relevant combinatorial processing, that is tied to the affix productivity of these transparent forms. More generally, this account is consistent with earlier psycholinguistic proposals (e.g., Clahsen et al., 2003; Marslen-Wilson, 2007; Marslen-Wilson et al., 1994), as well as with realization-based linguistic accounts (e.g., Anderson 1992), which posit that derivational rules map the entry of the stem onto the derived form.

These conclusions, if correct, suggest significant cross-linguistic variation in the extent to which derivationally complex forms are represented and accessed by domain-general bihemispheric systems, and in their degree of engagement with the more domain-specific left perisylvian system. For Italian, it is only the opaque non-productive forms that fully fit the picture of the derived word as a non-decomposed whole form that interacts primarily with the bilateral fronto-temporal system, and whose dominant processing signature is the cohort competition that it generates. The opaque forms with productive affixes, while also generating bilateral cohort competition effects, trigger a greater degree of decompositional activity, being affected by semantic relatedness and affix productivity. This activity, however, may represent bottom-up processes of mis-segmentation, driven by the presence of the productive affix, rather than reflecting the representation of the target item itself. The fully transparent productive forms, with a decompositional representational structure, and strongly reduced cohort competition effects, also activate bilateral temporal regions, but in addition engage left perisylvian processes likely to be related to their decompositional structure. Whether this simply reflects the greater combinatorial complexity of Italian derived forms, relative to English, cannot be determined at present.

A final major dimension of cross-linguistic variation involves the centrality, or otherwise, of semantic transparency in determining whether or not a derived form representationally incorporates its stem. For Italian, as for English and Polish, the semantic dimension seems the principal determinant. For a Semitic language such as Arabic, with its nonconcatenative word-formation processes, behavioural priming between two forms does not depend on semantic transparency. It is driven instead by the presence of a shared morpheme (the root or the word pattern) between prime and target (Boudelaa & Marslen-Wilson, 2015), indicating that representational overlap between different lexemes can be based on the morphosyntactic rather than the semantic properties of the relationship between them. A more general account of how morphological complexity is neurally represented across the world's languages will have to take on board this apparently fundamental difference in the basic principles in terms of which these representations are organised in different language families.

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Table 1. *Experimental design and stimulus properties.*

		Stem properties			*Suffix properties*		
Condition		*Embedded* stem	*Semantic Relatedness*	*Freq ratio*	*Suffix*	*Productive*	*Corpus-based Productivity*
1	Transparent productive (*libr-eria*)	Yes	4.6	1.10	Yes	Yes	0.022
2	Transparent non-productive (*pin-eta*)	Yes	4.5	1.07	Yes	No	0.008
3	Opaque productive (*tomb-ino*)	Yes	2	1.10	Yes	Yes	0.031
4	Opaque non-productive (*prem-ura*)	Yes	1.9	1.18	Yes	No	0.009
5	Simple (*libro*)	No	n/a	n/a	No	n/a	n/a

Relatedness = average pretest scores of judged semantic relatedness (0 – 5) between the whole word and the embedded stem; Freq ratio = ratio of log stem frequency to log of whole form lemma frequency.

Table 2. *Activation coordinates for general lexical processing.*

Regions	*Cluster Extent*	*Voxel Z*	*Coordinates* *x*	*y*	*z*
All words -MuR					
L Middle Temporal Gyrus (BA 21)	5182	6.62	-62	-12	-2
L Superior Temporal Gyrus (BA 22)		6.14	-64	-10	2
L Middle Temporal Gyrus (BA 21)		5.90	-64	-28	4
R Middle Temporal Gyrus (BA 21)	3619	6.62	68	-26	0
R Superior Temporal Gyrus (BA 22)		6.61	62	-10	0
R Superior Temporal Pole (BA 22)		6.30	54	14	-18
L Inferior Frontal Gyrus (BA 47)	140	4.58	-42	30	-6
L Inferior Frontal Gyrus (BA 45)		4.27	-52	12	22
L Inferior Frontal Gyrus (BA 44)		3.45	-54	30	18
R Inferior Frontal Gyrus (BA 47)	267	4.29	62	14	26
R Inferior Frontal Gyrus (BA 45)		4.10	60	18	26
R Rolandic Operculum		3.48	62	6	16

Table 3. *Activation coordinates for five groups of derivationally complex and simple words.*

Regions	*Cluster Extent*	*Voxel Z*	*Coordinates* *x*	*y*	*z*
(A) Transparent productive - MuR					
L Middle Temporal Gyrus (BA21)	2302	6.44	-62	-12	0
L Superior Temporal Pole (BA 38)		4.56	-56	10	-12
L Superior Temporal Gyrus (BA22)		3.40	-66	-32	20
R Superior Temporal Gyrus(BA 22)	3109	6.37	64	-10	-2
R Middle Temporal Gyrus (BA22)		6.27	68	-24	-2
R Superior Temporal Gyrus(BA 22)		5.57	60	-2	-8
(B) Transparent non-productive - MuR					
L Middle Temporal Gyrus (BA21)	2053	6.15	-62	-30	2
L Middle Temporal Gyrus (BA21)		5.81	-64	-40	2
L Middle Temporal Gyrus (BA21)		5.74	-56	-24	-2
R Superior Temporal Gyrus(BA 22)	2173	6.40	62	-12	0
R Middle Temporal Gyrus (BA22)		5.75	68	-26	0
R Middle Temporal Gyrus (BA22)		5.54	58	-30	2
L Inferior Frontal Gyrus (BA 47)	353	4.30	-46	28	-6
(C) Opaque productive - MuR					

L Middle Temporal Gyrus (BA 22)	3183	6.74	-62	-12	0
L Superior Temporal Pole (BA 38)		4.96	-52	8	-14
L Inferior Frontal Gyrus (BA 44)		4.17	-52	12	20
L Inferior Frontal Gyrus (BA 45)		4.02	-42	26	-2
R Superior Temporal Gyrus (BA 21)	2717	6.61	64	-12	2
R Superior Temporal Gyrus (BA 21)		5.97	66	-28	2
R Superior Temporal Gyrus (BA 21)		5.64	60	-18	-6
(D) Opaque non-productive - MuR					
L Superior Temporal Gyrus (BA 21)	6383	7.18	-62	-10	2
L Middle Temporal Gyrus (BA 22)		6.85	-62	-28	4
L Superior Temporal Pole (BA 38)		5.48	-56	12	-12
L Inferior Frontal Gyrus (BA 44)		4.76	-50	14	22
L Inferior Frontal Gyrus (BA 47)		4.95	-48	32	-5
L Inferior Frontal Gyrus (BA 45)		4.32	-40	28	8
R Superior Temporal Gyrus (BA 21)	5117	6.83	70	-24	2
R Middle Temporal Gyrus (BA 22)		6.66	56	-44	8
R Superior Temporal Gyrus (BA 21)		6.61	62	-8	0
R Inferior Frontal Gyrus (BA 44)		5.51	52	24	24
R Inferior Frontal Gyrus (BA 47)		3.96	52	28	-6
(E) Simple - MuR					
L Middle Temporal Gyrus (BA 22)	4382	6.60	-60	-14	-4
L Middle Temporal Gyrus (BA 22)		5.64	-66	-38	4

L Superior Temporal Pole (BA 38)		5.25	-56	12	-14
L Inferior Frontal Gyrus (BA 47)		4.68	-36	26	-6
L Inferior Frontal Gyrus (BA 45)		4.37	-44	12	26
L Inferior Frontal Gyrus (BA 44)		4.18	-48	10	22
R Middle Temporal Gyrus (BA 22)	3726	5.62	58	-22	-4
R Superior Temporal Pole (BA 38)		5.85	62	-12	-4
R Superior Temporal Gyrus (BA 21)		5.71	54	6	-16
R Inferior Frontal Gyrus (BA 44)	410	5.80	62	16	20
R Inferior Frontal Gyrus (BA 44)		5.73	60	16	28
R Inferior Frontal Gyrus (BA 45)		4.32	48	20	22

Table 4. *Activation coordinates for overall contrasts between opaque and transparent words.*

Regions	*Cluster Extent*	*Voxel Z*	*Coordinates* *x*	*y*	*z*
(A) All Opaque - All Transparent					
L Superior Temporal Gyrus (BA 21)	1450	5.07	-60	-14	2
L Superior Temporal Gyrus (BA 21)		4.89	-54	-22	4
L Middle Temporal Gyrus (BA 22)		4.40	-60	-42	8
R Inferior Frontal Gyrus (BA 45)	607	4.67	44	30	10
R Inferior Frontal Gyrus (BA 44)		4.59	58	20	28
R Inferior Frontal Gyrus (BA 45)		4.46	48	24	24
R Middle Temporal Gyrus (BA 22)	1666	4.63	60	-34	4
R Superior Temporal Gyrus (BA 21)		4.63	64	-20	8
R Superior Temporal Gyrus (BA 21)		4.52	50	-42	14
L Inferior Frontal Gyrus (BA 44)	224	4.21	-44	8	24
L Inferior Frontal Gyrus (BA 44)		4.09	-38	4	30
L Inferior Frontal Gyrus (BA 44)		3.81	-54	12	28
L Inferior Frontal Gyrus (BA 45)	134	4.16	-40	30	8
L Inferior Frontal Gyrus (BA 45)		3.25	-48	22	18
(B) Opaque non-productive - Transparent non-productive					
R Superior Temporal Gyrus (BA 21)	3152	5.74	68	-26	6
R Superior Temporal Gyrus (BA 21)		5.10	48	-24	2

R Superior Temporal Gyrus (BA 21)		5.05	58	-24	4
L Middle Temporal Gyrus (BA 22)	2613	5.68	-48	-22	0
L Middle Temporal Gyrus (BA 22)		5.36	-54	-16	-2
L Superior Temporal Gyrus (BA 21)		4.96	-52	-40	14
R Inferior Frontal Gyrus (BA 45)	820	4.91	56	22	22
R Inferior Frontal Gyrus (BA 45)		4.28	46	28	14
R Precentral Gyrus (BA 6)		4.27	52	14	38
L Inferior Frontal Gyrus (BA 45)	796	4.60	-44	12	26
L Precentral Gyrus (BA 6)		4.40	-38	2	36
L Inferior Frontal Gyrus (BA 45)		4.27	-44	26	12
(C) Opaque non-productive - Opaque productive					
L Superior Temporal Gyrus (BA 21)	1597	5.20	-56	-26	4
L Middle Temporal Gyrus (BA 22)		4.58	-66	-44	8
L Middle Temporal Gyrus (BA 22)		4.45	-64	-54	10
R Middle Temporal Gyrus (BA 22)	1477	5.08	44	-46	20
R Superior Temporal Gyrus (BA 21)		5.00	70	-24	8
R Superior Temporal Gyrus (BA 21)		3.81	60	-8	-6
R Inferior Frontal Gyrus (BA 47)	265	4.43	40	28	-6
R Inferior Frontal Gyrus (BA 45)		4.01	46	30	10

Table 5. *RSA analyses for Lexical Competition. Coordinates and voxel-level peak significance values (p) for each activation cluster.*

Regions	*Cluster Extent*	*Voxel-level P*	*Pseudo-t*	*Coordinates* *x*	*y*	*z*
(A) Lexical Competition (all words)						
L Superior Temporal Gyrus (BA 21)	953	0.0043	6.98	-60	-16	6
L Middle Temporal Gyrus (BA 22)		0.0043	4.77	-42	-58	-4
R Superior Temporal Gyrus (BA 21)	818	0.0043	4.99	60	-13	6
R Middle Temporal Gyrus (BA 22)		0.0074	3.91	57	-55	2
R Superior Temporal Gyrus (BA 21)		0.0043	3.75	60	-52	21
R Ant Cingulate (BA 24)	371	0.0060	4.86	3	23	29
R Ant Cingulate (BA 24)		0.0199	3.81	9	38	18
L Ant Cingulate (BA 24)		0.0199	3.31	-3	35	14
R Fusiform (BA 37)	110	0.0194	3.10	33	-55	-16
R Fusiform (BA 20)		0.0103	3.04	39	-31	-20
L Inferior Frontal Gyrus (BA 47)	29	0.0263	3.15	-18	8	-20
L Insula		0.0254	2.51	-27	23	-5
L Inferior Temporal Gyrus (20)		0.0377	3.09	-54	-16	-28
R Inferior Frontal Gyrus (BA 44)	133	0.0304	3.02	51	20	10
R Precentral Gyrus (BA 6)		0.0361	2.27	54	2	36
(B) Lexical Competition (opaque words)						
L Superior Temporal Gyrus (BA 21)	346	0.0043	6.55	-60	-16	6

L Superior Temporal Gyrus (BA 21)		0.0064	3.93	-42	-34	14
R Superior Temporal Gyrus (BA 21)	302	0.0043	5.67	63	-10	6
R Superior Temporal Gyrus (BA 21)		0.0043	5.02	63	-25	10

Table 6. *RSA Analyses for Semantic Relatedness. Coordinates and voxel-level peak significance values (p) in each activation cluster.*

Regions	*Cluster Extent*	*Voxel-level P*	*Pseudo -t*	*Coordinates* *x*	*y*	*z*
(A) Semantic Relatedness (all words)						
L Fusiform (BA 20)	1034	0.0032	5.13	-18	-37	-16
L Fusiform (BA 20)		0.0023	4.51	-36	-16	-24
R Fusiform (BA 20)	724	0.0023	5.39	39	-16	-28
R Inferior Temporal Gyrus (BA 20)		0.0023	4.78	54	-16	-28
R Inferior Frontal Gyrus Orbitalis (BA 47)	678	0.0023	5.06	27	29	-12
R Inferior Frontal Gyrus Orbitalis (BA 47)		0.0023	4.55	18	21	-20
R Anterior Cingulate (BA 32)	483	0.0023	4.85	9	35	29
R Middle Temporal Gyrus (BA 22)	365	0.0023	5.67	57	-58	-1
L Inferior Temporal Gyrus (BA 20)	134	0.0079	3.84	-51	-64	-5
L Middle Temporal Gyrus (BA 22)		0.0201	3.23	-40	-61	-5
R Middle Temporal Gyrus (BA 22)	86	0.0182	2.67	45	-55	20
(B) Semantic Relatedness (opaque words)						
L Inferior Temporal Gyrus (BA 20)	1875	0.0022	7.05	-45	11	-35
R Inferior Temporal Gyrus (BA 20)	1363	0.0022	6.46	54	-19	-28
R Inferior Temporal Gyrus (BA 20)		0.0022	5.23	33	5	-39
R Anterior Cingulate (BA 32)	546	0.0022	5.75	9	35	29

R Inferior Frontal Gyrus Orbitalis (BA 47)	534	0.0022	5.43	48	17	6
(C) Semantic Relatedness (opaque productive words)						
Left Inferior Frontal Gyrus (BA 45)	1692	0.0039	5.40	-42	38	14
Left Inferior Frontal Gyrus (BA 47)		0.0062	5.27	-39	47	2
R Inferior Temporal Gyrus	1294	0.0053	5.02	57	-19	-28
R Fusiform		0.0039	5.01	42	-22	-24
R Inferior Temporal Gyrus		0.0074	4.26	54	-52	-5
R Insula	217	0.0062	4.10	33	17	-5
R Inferior Frontal Gyrus (BA 45)		0.0126	2.45	48	32	14
R Inferior Frontal Gyrus (BA 44)		0.04580	2.39	54	17	2
L Ant Cingulate	123	0.0067	3.80	-9	44	2
R Inferior Frontal Gyrus (BA 44)	45	0.0253	2.97	45	14	29
R Inferior Frontal Gyrus (BA 44)		0.0364	2.62	36	8	32
R Precentral		0.0373	2.53	45	8	36
(D) Semantic Relatedness (opaque non-productive words)						
L Fusiform	617	0.0145	5.11	-36	-55	-9
L Fusiform		0.0161	4.54	-30	-49	-16
L Middle Temporal Gyrus (BA 22)		0.0145	4.49	-41	-58	14
R Ant Cingulate	211	0.0291	3.74	3	41	2
L Inferior Frontal Gyrus (BA 45)	181	0.0161	3.82	-42	20	6

L Inferior Frontal Gyrus (BA 47)		0.0294	2.92	-36	35	-16
R Inferior Temporal Gyrus (BA 20)	172	0.0145	4.88	48	-55	-9
R Precentral (BA 6)	110	0.0167	4.65	51	5	32
R Inferior Frontal Gyrus (BA 47)	95	0.0145	3.31	27	32	-16
R Inferior Frontal Gyrus (BA 45)	35	0.0294	3.54	51	35	-1
R Inferior Frontal Gyrus (BA 45)		0.0362	2.57	39	35	14

Table 7. *RSA Analyses for Suffix Productivity. Coordinates and voxel-level peak significance values (p) in each activation cluster.*

Regions	*Cluster Extent*	*Voxel-level P*	*Pseudo-t*	*Coordinates*		
				x	*y*	*z*
(A) Suffix productivity (transparent words)						
R Middle Temporal Gyrus (BA 22)	1031	0.0083	6.06	57	-31	2
R Superior Temporal Gyrus (BA 21)		0.0108	4.55	60	-7	-1
R Superior Temporal Pole (BA 38)		0.0083	4.30	57	11	-5
L Superior Temporal Gyrus (BA 21)	982	0.0083	6.28	-60	-19	6
L Inferior Frontal Opercularis (BA 44)		0.0085	4.15	-60	5	14
L Inferior Frontal Opercularis (BA 44)		0.0213	3.37	-45	11	29
(B) Suffix productivity (transparent productive words)						
R Middle Temporal Gyrus (BA 22)	253	0.0380	4.88	48	-34	2
R Middle Temporal Gyrus (BA 22)		0.0384	4.84	57	-28	2
L Superior Temporal Gyrus (BA 21)	157	0.0427	4.03	-60	-22	6
L Superior Temporal Gyrus (BA 21)		0.0403	4.03	-54	-7	-9

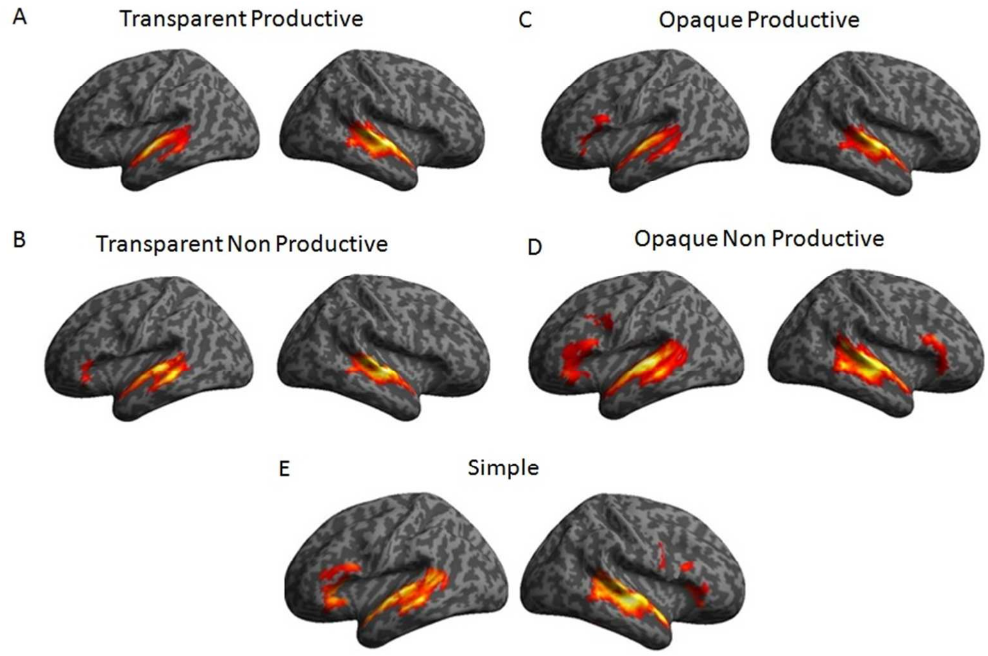

Figure 1. Univariate results showing activations for each experimental condition contrasted against the Musical Rain (MuR) baseline: a. Transparent Productive Words; b. Transparent Non-productive Words; c. Opaque Productive Words; d. Opaque Non-productive Words; e. Simple Words. Results are shown at a threshold of p<0.001 uncorrected, with cluster level correction for FDR 0.05.
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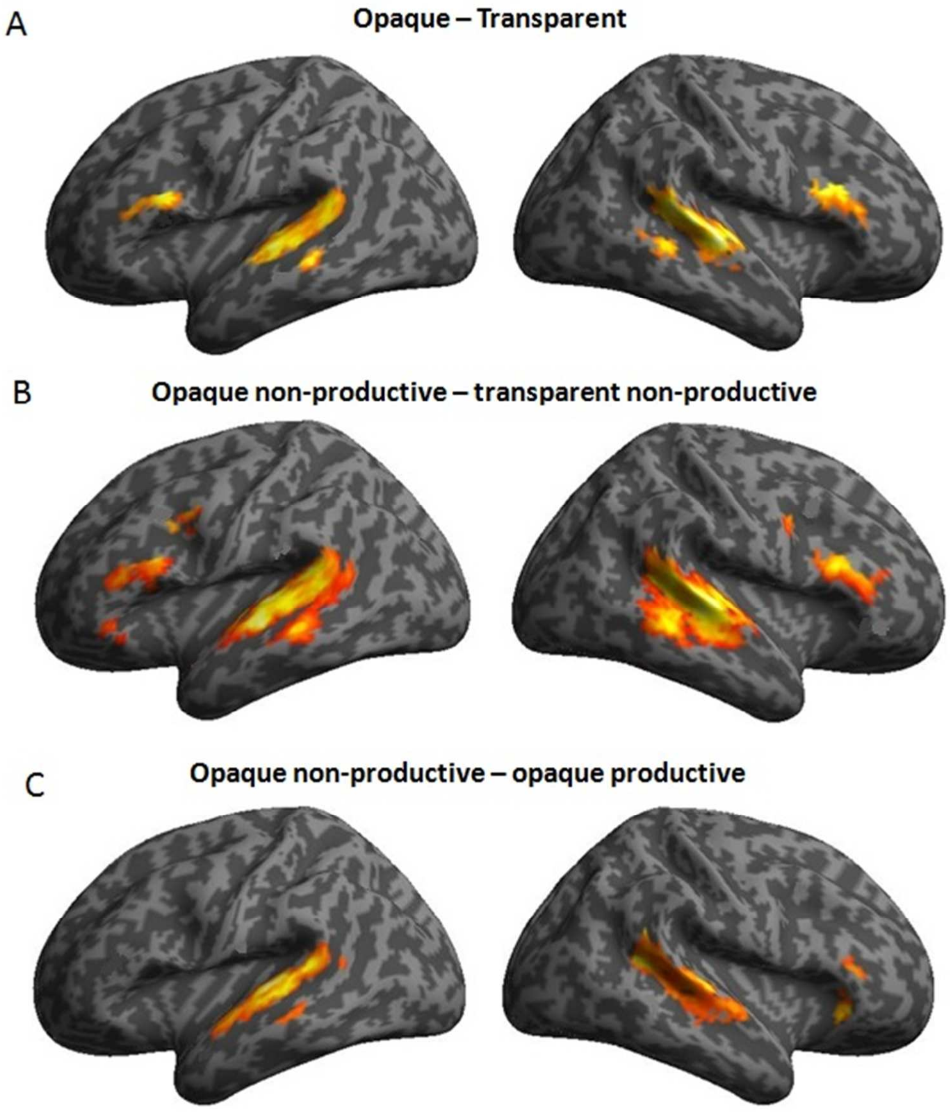

Figure 2. Univariate results for global comparisons between conditions: a. All Opaque words vs. all Transparent words; b. Opaque Non-productive words compared with Opaque Productive words; c. Opaque Non-productive words compared with Transparent Non-productive words. Results are shown at a threshold of p<0.001 uncorrected, with cluster level correction for FDR 0.05.
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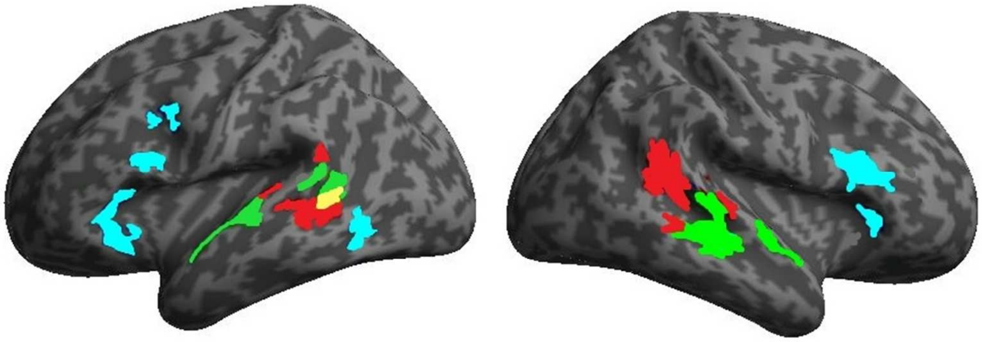

Figure 3. Parametric modulation results for the Opaque word sets: a. Semantic Relatedness (in red); b. Lexical Competition (in green); c. Suffix Productivity (in blue). Results are shown at a threshold of p<0.001 uncorrected, and at a more lenient threshold of p<0.01 for Suffix Productivity. Only left middle temporal activations to Semantic Relatedness and Lexical Competition survived correction for FDR 0.05.
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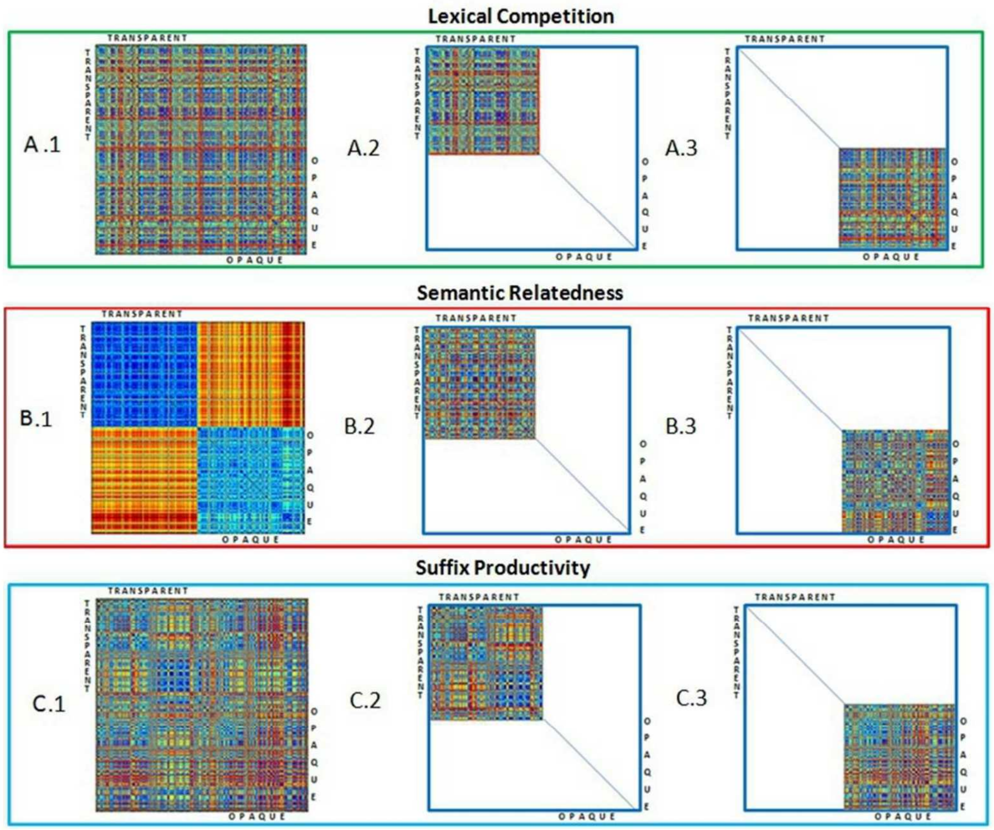

Figure 4. The six model Representational Dissimilarity Matrices (RDMs) used in the RSA analyses: a. Lexical Competition RDMs for A.1. All words, A.2. Transparent words and A.3. Opaque words; b. Semantic Relatedness RDMs for B.1. All words, B.2. Transparent words and B.3. Opaque words; c. Suffix Productivity RDMs for C.1. All words, C.2. Transparent words and C.3. Opaque words.
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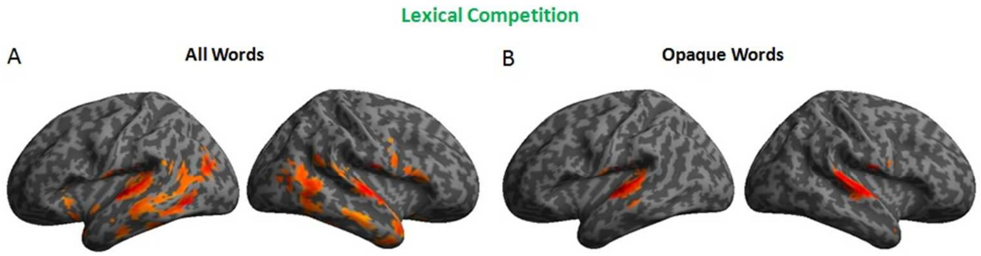

Figure 5. RSA Lexical Competition analyses: Brain areas showing significant model fit for A. All words and B. Opaque words. All results are significant at FDR 0.05.
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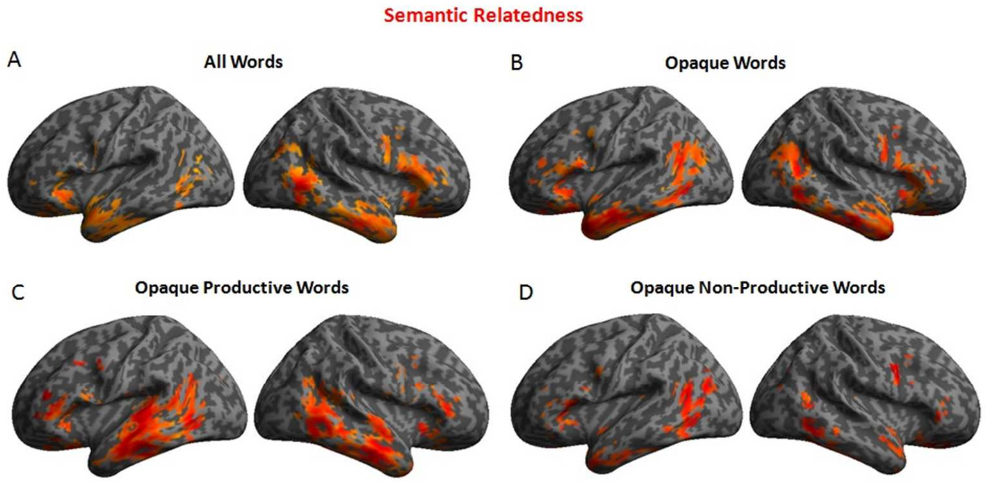

Figure 6. RSA Semantic Relatedness analyses: Brain areas showing significant model fit for A. All words; B. Opaque words; C. Opaque Productive words; D. Opaque Non-productive words. All results are significant at FDR 0.05.
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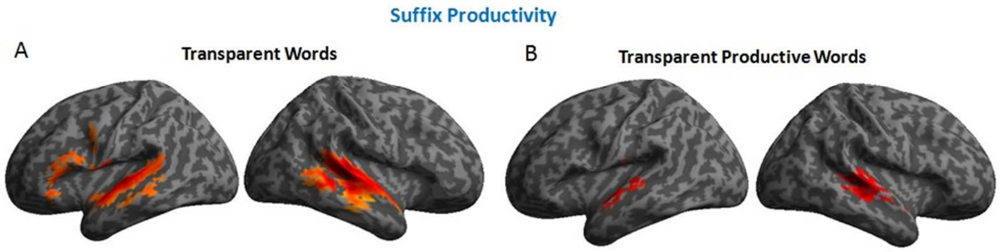

Figure 7. RSA Suffix Productivity analyses: Brain areas showing significant model fit for A. Transparent words; B. Transparent Productive words. All results are significant at FDR 0.05.
252x69mm (96 x 96 DPI)