Published in final edited form as:

Brain Lang. 2019 July ; 194: 65–76. doi:10.1016/j.bandl.2019.04.005.

Neurocognitive correlates of category ambiguous verb processing: The single versus dual lexical entry hypotheses

Sladjana Lukic^{a,b,*}, Aya Meltzer-Asscher^e, James Higgins^{a,d}, Todd B. Parrish^{a,d}, Cynthia K. Thompson^{a,b,c}

^aNorthwestern University, Center for the Neurobiology of Language Recovery, United States

^bNorthwestern University, Department of Communication Sciences and Disorders, School of Communication, United States

^cNorthwestern University, Neurology, Feinberg, School of Medicine, United States

^dNorthwestern University, Radiology, United States

^eTel Aviv University, Department of Linguistics, Sagol School of Neuroscience, Israel

Abstract

Word-class ambiguous words engender greater processing time and fMRI (BOLD signal) activation than unambiguous ones. Theoretical accounts of this phenomenon suggest that words with multiple meanings (1) are associated with multiple lexical entries and thus require greater selection demands, or (2) undergo computationally expensive grammatical processes that convert words from one word-class to another. Using an fMRI grammaticality judgment task, we tested these accounts by examining word-class ambiguous polysemic (e.g., *brush*) and homonymic (e.g., *bear*) verbs, and unambiguous verbs (e.g., *bake*). Results showed that ambiguous verbs evoked longer response times and greater neural activation in the left inferior frontal and parietal gyri. However, homonymic verbs also showed increased left inferior frontal and temporal neural activations compared to polysemic verbs. This indicates that rather than having multiple lexical representations like homonyms, polysemic verbs may share a core representation with their noun counterparts.

Keywords

fMRI; Word-class; Categorical ambiguity; Conversion/zero-morphology; Semantic control

1. Introduction

The neural basis of verb processing has been extensively studied over the past several years with functional magnetic resonance imaging (fMRI) (e.g., Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; den Ouden, Fix, Parrish, & Thompson, 2009; Friederici, 2011; Friederici & Kotz, 2003; Malyutina & den Ouden, 2017; Shetreet, Palti, Friedmann, &

*Corresponding author at: Memory and Aging Center, Department of Neurology, University of California San Francisco, 675 Nelson Rising Lane, Suite 190, San Francisco, CA 94158, United States. Sladjana.lukic@ucsf.edu (S. Lukic).

Hadar, 2007; Thompson et al., 2007, 2010). In addition, a substantial body of work has focused on word-class distinctions (i.e., differences between verb and noun processing) (e.g., Berlingeri et al., 2008; Shapiro et al., 2005; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011). Notably, inconsistent neural activation patterns have been reported across studies, with some finding overlapping regions of activation for the two word classes and others showing distinct (albeit, in many cases, inconsistent) activation patterns (Crepaldi, Berlingeri, Paulesu, & Luzzatti, 2013; Crepaldi et al., 2011). In their review of 15 neuroimaging studies contrasting activation associated with verbs versus nouns, Crepaldi et al. (2011) noted that one reason for this heterogeneity may relate to differences in neuroimaging tasks that have been used across studies, ranging from lexical decision to picture naming. Another important observation is that most studies have limited their investigation to action verbs and object nouns, which represent only subsets of these large word classes, as words within both categories vary with regard to their morphosyntactic and semantic properties.

In this paper, we focus on one interesting property of verbs, namely category ambiguity. Some verbs are categorically unambiguous, associated with only one word-class (e.g., *bake* is an unambiguous verb) (1), whereas others are categorically ambiguous (e.g., the word *bear* may be used as a verb or a noun). Moreover, categorically ambiguous verbs may be homonymous (e.g., *bear* (2a)), referring to two unrelated meanings, or polysemous (e.g., *brush* (2b)), referring to two related senses.

1. Unambiguous verb (*bake*) = the event of cooking
2. Ambiguous
 - a. Homonymic verb (*bear*) = the event of supporting/an animal
 - b. Polysemic verb (*brush*) = the event of grooming/an object used for grooming

How or if these properties of verbs are represented in the mental lexicon and/or affect neurocognitive processing is unclear. On some accounts, polysemous verbs such as *brush* are thought to be result of category conversion, a grammatical word-form process which converts the category of a word without visible morphological change (e.g., Don, 2005; Lipka, 1986)¹. Consequently, when the noun form '*brush*' shifts to the verb 'to *brush*' by conversion, the verb exhibits a semantic dependence with the base form noun (e.g., expresses an action using the noun as instrument). This suggestion is in line with Single Entry (Nunberg, 1979) and *Fully Decompositional* (Taft & Foster, 1975) accounts, which suggest that only base forms are stored in the mental lexicon, and grammatical operations derive one category from the other online.

Alternatively, other accounts suggest that polysemous verbs do not engage online grammatical word-form processes. Rather, whole words are stored separately in the mental lexicon. This Dual Entry hypothesis is in line with *Full Listing* accounts (Jackendoff, 1976,

¹In the theoretical literature, some researchers refer to this process as conversion, whereas others refer to it as (zero-) derivation. This distinction is irrelevant in the current paper, and we used the term "grammatical word-form process" to refer to conversion/derivation terms interchangeably.

2002) and also compatible with more contemporary *Amorphous Morphology* theories (Anderson, 1992; Aronoff, 1994) and related processing and computational models (e.g. Baayen, Milin, Juravić, Hendrix, & Marelli, 2011; Ramscar & Port, 2016; Seidenberg & Gonnerman, 2000). Dual Entry theories reject the role of morphemes and take the lexeme, rather than the morpheme, as the basic unit in representation and processing. Thus, words are directly associated with their meaning representation, without the mediation of morphemes.

To summarize, according to Dual Entry theories, both polysemic and homonymic verbs entail two listings – a verb form and a noun form. In contrast, under the Single Entry account, the two ambiguous verb categories entail different representations: homonymic verbs like *bear* are associated with two entries, whereas polysemic verbs like *brush* are associated with only one stored entry, the noun, with the verb form undergoing online grammatical word-form processes. Though these are extremely productive in English, the associated processing costs are unclear.

Previous studies on ambiguity processing have shown a processing cost associated with ambiguous words (see Eddington & Tokowicz, 2015 for review). This processing cost is affected by semantic and syntactic properties of the different meanings, with greater processing difficulty for ambiguous words with semantically unrelated meanings (homonymy) compared to related ones (polysemy), and for those with two meanings within the same word-class compared to different word-classes (e.g., Beretta, Fiorentino, & Poeppel, 2005; Mirman, Strauss, Dixon, & Magnuson, 2010; Rodd, Gaskell, & Marslen-Wilson, 2002). Klepousniotou and Baum, using priming and simple lexical decision tasks, presented two types of homonymous words (balanced (*panel*) and unbalanced (*coach*) frequency) and polysemous words (metonymic like *rabbit – hop vs. rabbit – stew*, and metaphorical like *lip – the organ of the body vs. lip – an edge of a vessel*) in sentential contexts (2002) and in isolation (2007). Results showed that homonymous words engendered greater processing cost compared to metonymic polysemy (i.e., significantly reduced priming effects and response time) and metaphorical polysemy fell somewhere between metonymy and homonymy.

In addition to these behavioral costs, neuroimaging studies manipulating semantic ambiguity have found left and/or right frontal as well as temporal activation under conditions of increased competition between multiple meanings (Burton, Krebs-Noble, Gullapalli, & Berndt, 2009; Copland, de Zubicaray, McMahon, & Eastburn, 2007; Gennari, MacDonald, Postle, & Seidenberg, 2007; Mason & Just, 2007; Rodd, Davis, & Johnsrude, 2005; Zemleni, Renken, Hoeks, Hoogduin, & Stowe, 2007; also see Binder, Desai, Graves, & Conant, 2009; Eddington & Tokowicz, 2015 for reviews), suggesting a network for semantic control processes (e.g., Thompson-Schill, Bedny, & Goldberg, 2005). Using an auditory grammaticality judgment task, Burton et al. (2009) found an effect of word-class ambiguity in the left posterior inferior frontal gyrus (IFG) (BA 44, 45; pars opercularis and triangularis), with greater activation for polysemic words (e.g., *the/to smell*) compared to unambiguous words (e.g., *the song, to send*). Gennari et al. (2007) also found that polysemic words (e.g., *brush*) elicited more activity in the left IFG (BA 45, 47; pars triangularis and orbitalis). These and other researchers also have reported posterior temporal lobe activation

(i.e., posterior middle temporal gyrus (MTG) and superior temporal gyrus (STG)) for processing categorically polysemous versus unambiguous words (Burton et al., 2009; Gennari et al. (2007); ; . Similar patterns have been reported for between versus within word-class homonymic words. Grindrod, Garnett, Malyutina, and den Ouden (2014), using a lexical decision task, found syntactic similarity effects in the left anterior IFG (BA 47; pars orbitalis), with greater activation for noun-verb (e.g. rock, which has unrelated noun and verb readings) than noun-noun (e.g. *match*, which has two unrelated nouns readings) homonyms, suggesting greater selection demands between categories (compared to within category). Meaning dominance effects also have been observed in the left MTG and STG for homonyms, with greater activation observed for balanced than unbalanced homonyms (Grindrod et al., 2014).

Collectively, the literature suggests that left anterior IFG (BA 47; pars orbitalis) and posterior IFG (BA 45; pars triangularis) mediate top-down controlled retrieval and selection of lexical representations, respectively (see Lau, Phillips, & Poeppel, 2008). Left temporal areas, found to coactivate with the frontal cortex, also play a role in control processes during meaning retrieval in addition to lexical representation/activation (e.g., Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Kuperberg, Sitnikova, & Lakshmanan, 2008; Noppeney, Phillips, & Price, 2004; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001; Wawrzyniak et al., 2017). Moreover, Whitney, Jefferies, and Kircher (2011) identified a functional dissociation between processes related to semantic control and representation in posterior and inferior aspects of the temporal cortex during ambiguity processing. Whereas activation of multiple concepts of homonyms resulted in left inferior temporal (ITG) activation, selection between the concepts, requiring enhanced semantic control, resulted in posterior MTG activity. Lastly, the dorsal part of the left inferior frontal and parietal lobes, and a region in the posterior inferior temporal lobe, are part of the left fronto-parietal network (FPN) and are thought to serve the semantic control system (see a recent three-network model of semantic processing in Xu, He, & Bi, 2017; see also Chiou, Humphreys, Jung, & Ralph, 2018).

To date, only one neuroimaging study has attempted to manipulate category conversion (Pliatsikas, Wheeldon, Lahiri, & Hansen, 2014). In this study, the authors compared neural activation patterns elicited by what they termed “one-step” (*bouncing*) versus “two-step” (*brushing*) derived words, as well as monomorphemic control words (*grumble*). According to the authors, one-step words entail an event-denoting base, and are therefore directly derived from their verb base-form (e.g., bounce-V > *bouncing*), whereas two-step words have an object-denoting base and are, accordingly, derived via an additional step of conversion/zero-derivation from their base-form noun to a verb (e.g., brush-N > brush-V > *brushing*). Two main findings were reported: (1) increased brain activity within the left IFG and temporo-occipital gyrus, and the bilateral fusiform gyrus (FG) for morphologically inflected words (*bouncing*, *brushing*) compared to control words (*grumble*), and (2) increased activity within the left posterior IFG (BAs 44, 45; pars opercularis and triangularis), for “two-step” words like *brushing* compared to “one-step” words like *bouncing*. The authors suggested that processing in these frontal areas is not limited to decomposition of overt affixes (Meinzer, Lahiri, Flaisch, Hannemann, & Eulitz, 2009) but also reflects covert derivational complexity, i.e. conversion/zero-derivation.

However, the study of Pliatsikas et al. (2014) has several limitations. The authors used a questionnaire (rating of object or action meaning) to classify their forms as event-based or object-based. However, their classifications were not completely compatible with standard linguistic tests, which have been established to determine the base form of zero-derived words. These include Meyer's Root Suffixation test (1984), whereby noun-derived forms allow certain classes of suffixes (those attaching to nouns, such as e.g. *-y*), but not others (those attached to verbs, e.g., *-ive*), whereas verb-derived forms exhibit the opposite pattern. Another set of tests, introduced in Marchand (1964) and Clark and Clark (1979) exploit the semantic relation between the noun-form and the verb-form; for example, according to Clark and Clark, noun-derived verbs must stand in one of six specific relations to the base noun (e.g. involve the tool denoted by the noun, as in the case of *brush*). In contrast to this, in Pliatsikas et al. (2014), *scout* and *spice*, for example, were both classified as object-based, even though according to these linguistic tests only *spice* is noun-derived verb whereas the base form of *scout* is a verb, with the noun *scout* derived from the action of scouting. Given these confounds, it is difficult to interpret the increased activation for "two-step" words as unequivocally reflecting the processing cost of zero-derivation, rather than, for example, that of lexical selection between the noun and verb representations (as in Grindrod et al., 2014).

The goal of the present study was to identify patterns of neural activation associated with the computational and/or representational properties of verbs, teasing apart activation arising from grammatical word-form processes (i.e., conversion/zero-derivation) as opposed to that associated with solving semantic (categorical) ambiguity. Using fMRI and a grammaticality judgment task (GJT), the study examined the neural mechanisms associated with processing unambiguous verbs (*bake*), polysemic noun-derived verbs (*brush*), and homonymic verbs (*bear*) controlled for noun and verb frequency.

The Dual Entry account, which holds that the two meanings of word-class ambiguous words are listed separately in the mental lexicon, predicts similar processing routines for homonymic and polysemic words (i.e., the noun and verb forms co-activate, with no effect of grammatical computation). However, because the two verb categories differ with regard to the semantic similarity between their noun and verb form – to *brush* and the *brush* are semantically related, whereas to *bear* and the *bear* are semantically unrelated – lesser competition demands between forms are expected for the polysemic words compared to the homonymic words. Therefore, this hypothesis predicts graded activation in regions involved in semantic retrieval/selection and control (i.e., in BA47/45; IFG pars orbitalis/triangularis), with the greatest activation for homonymic verbs, lesser activation for polysemic verbs, and the least activation for unambiguous verbs (in line with the aforementioned ambiguity studies, e.g., Grindrod et al., 2014; Thompson-Schill et al., 2005).

The Single Entry account makes different predictions. Like the Dual Entry account, it predicts greater activation for homonymic verbs as opposed to polysemic and unambiguous verbs in regions involved in controlled semantic retrieval/selection as well as in lexical representation/activation (i.e., in ITG; Whitney et al., 2011). However, it also predicts differential activation for polysemic compared to unambiguous or to homonymic verbs, associated with grammatical word-form processes. This differential activation is predicted to appear in posterior IFG (BA 44/45; IFG pars opercularis/triangularis), argued to support

(derivational as well as inflectional) morphological processes (based on Pliatsikas et al., 2014, Marslen-Wilson & Tyler, 2007, Meinzer et al., 2009). See Table 1 for a summary of the behavioral and neural predictions, as well as the assumptions regarding lexical statistics (e.g., the lemma and form frequencies), according to the different representational hypotheses.

2. Methods

2.1. Participants

Twenty right-handed, young healthy individuals took part in this study. All participants were monolingual English speakers with normal or corrected-to normal vision and hearing, and showed no history of psychiatric, neurological, speech, or language disorders. Participants were recruited from the Northwestern University student body and staff, as well as from residents within the greater Chicago area. All participants provided written informed consent approved by the Northwestern University Institutional Review Board. Two participants were excluded due to a technical problem with the scanner or due to claustrophobia. The remaining eighteen participants (9 females; age range = 19 to 28 years, $M = 24$; education range = 13 to 18 years, $M = 15$) were included in the analyses reported below.

2.2. Materials

The stimuli consisted of 63 experimental items, and 21 baseline items, each repeated twice. The study included three verb conditions, with 21 items in each: (1) unambiguous verbs with a single, verbal, lexical representation (to *bake*), (2) polysemic verbs ambiguous between a verb and a noun (to *brush*), and (3) homonymic verbs ambiguous between a verb and a noun (to *bear*). All verbs in condition 2 passed the linguistic diagnostics identifying verbs derived from nouns (rather than vice versa). Ambiguous verbs (conditions 2–3) were selected only if the noun and verb forms had: (a) identical orthographic and phonological form (i.e., all were homographs and homophones, respectively), and (b) near-equal form and lemma frequency of usage as a noun and as a verb (N/V ratio range: 0.8–1.1) based on the Corpus of Contemporary American English (COCA; Davies, 2008).

Note that the frequency and morphological family size (the total number of word types in which a morpheme occurs) for the two ambiguous verb categories are calculated differently under the Single Entry and Dual Entry accounts. For example, under the assumptions of the Single Entry account, lemma frequency is calculated differently for polysemic and homonymic verbs since in the homonymy case, lemma frequency (all word-form frequencies of words within an inflectional paradigm, i.e., *brush*, *brushes*, *brushed*, *brushing*) comes only from verbal uses, but in the polysemy case, there is a single stem for the noun and verb uses. However, under the assumptions of the Dual Entry account, lemma frequency is calculated based on only the verbal use in both cases. Importantly, lemma frequency and morphological family size calculated on the basis of the two accounts (single vs dual) were included as independent variables in two separate analyses of the data (see Data Analysis).

Table 2 presents the lexical statistics for the items in each verb condition. For ease of presentation, the table includes the statistics according to the Single Entry account. However,

under both accounts, the two ambiguous conditions were matched on their overall word-form frequency (the total number of tokens of a given word), lemma frequency, and morphological family size (the English Lexicon Project, <http://elexicon.wustl.edu/>; Balota et al., 2007).

To control the semantic relatedness between the noun and verb reading of the items, twenty native English speakers (8 females, M age = 25) were presented with noun and verb pairs (e.g., the fight/to fight) and were instructed to rate the degree of similarity between the meaning of the noun and the verb using a 7-point Likert-scale (1 = low similarity, 7 = high similarity). Two practice items were given. As intended, we found a significant difference between the two groups of verbs (condition 2 and 3) ($t = 11.81$, $p = .000$), in that the polysemous pairs ($N = 17$) had *similar meaning* ($M = 4.68$, $SD = 0.87$), while homonymous pairs *differed in meaning* ($M = 2.01$, $SD = 0.55$).

Finally, imageability ratings were collected for each verb using a rating questionnaire. Fifteen native English-speaking participants (10 females, M age = 28) were asked to rate on a 7-point Likert-scale (1 = low, 7 = high) the degree of imageability of the phrase “to + V” by indicating how easy it was to create a mental image for each experimental item. There were no significant differences between the verbs included in the three conditions for orthographic length and imageability. However, the unambiguous verb condition and the ambiguous verb conditions could not be matched on word-form frequency because unambiguous verbs tend to have lower frequencies than ambiguous verbs.

Experimental verbs were paired with to (e.g. to *bake*, to *brush*, to *bear*). In addition to the 63 experimental stimuli, 21 letter-string pairs (e.g., letter-string = bb bbbb) were selected and served as low-level baseline (repeated twice). An additional 42 items (verbs and letter-string pairs; 21 each) were included to create ungrammatical and non-matching trials in the grammaticality judgment task to parallel the grammatical experimental items and baseline letter-string pairs, respectively. For this, unambiguous verbs were paired with ‘the’ (*the build*) and the letter-string pairs included strings of different letters (ff bbbb). Finally, unambiguous nouns paired with ‘the’ (*the bell*) as well as with ‘to’ (*to belt*) were selected as fillers (21 each). Appendix A displays the complete list of stimuli for each condition.

2.3. Design

A rapid event-related design was selected for this study in order to account for (a) proper randomization of stimuli, (b) randomized inter-stimulus onsets, and (c) “jittered” randomly intervening rest intervals (NULL events). The study was comprised of two runs, each including 63 experimental items, 21 baseline items, and 42 filler stimuli, all in different orders, presented during a single session. Stimuli were randomized within each run using the OPTSEQ program (<http://surfer.nmr.mgh.harvard.edu/optseq>) to generate an optimized random order of all conditions. The ordering constraints were specified as follows: (1) no more than three consecutive trials of the same condition, (2) no more than four consecutive trials with the same response (match or mismatch), and (3) items from each condition were preceded by equal proportions of items from the other conditions. In addition, 61 randomized “jittered” NULL events (0–15 s) were inserted, using the OPTSEQ program and

TR = 1.6 s. This resulted in a varied onset of successive stimulus events, with randomly intervening rest intervals.

2.4. Procedure

Participants performed a task in which they decided whether the two-word sequences were grammatical or not (i.e., a grammaticality judgment task), and whether the two letter strings matched ('bb bbbb') or mismatched ('ff bbbb') (i.e., a matching judgment task). In each trial, the word or letter-string pair was visually displayed for 2.5 s, preceded by a fixation cross for 0.5 s and then followed by jittered, randomly intervening rest intervals (NULL events) lasting between 0 and 15 s (see Fig. 1). Participants were instructed to use their right hand and to respond by pressing with their index finger for a match, and with their middle finger for a mismatch. Participants performed practice trials (with feedback) before entering the scanner in order to become familiar with the task. The experiment was presented using E-Prime software version 2.0.8 (Bates, Maechler, & Bolker, 2012) on a Dell desktop computer running Windows XP Professional with an Intel Core 2Duo CPU processor.

2.5. fMRI data acquisition

A 3T Siemens Prisma scanner was used to obtain anatomical (T1-weighted) and functional (T2*-weighted) scans at the Center of Translational Imaging (CTI) at Northwestern University. The T1-weighted scan was acquired using an MP-RAGE sequence with the following parameters: time to repeat (TR) = 2300 ms, time to echo (TE) = 2.94 ms, flip angle = 9 degrees; matrix size = 256×256 ; field of view (FOV) = 256 mm; voxel size = $1 \times 1 \times 1$ mm; 176 slices. Functional scans were obtained with a T2* weighted echo planar sequence using the following parameters: TR = 1600 ms; TE = 20 ms, flip angle = 80 degrees; matrix size = 104×104 ; FOV = 208 mm; voxel size = $2 \times 2 \times 2$ mm; multiband acceleration factor of 2, 60 slices.

2.6. Data analysis

2.6.1. Behavioral data analysis—Accuracy (proportion correct) and RT (milliseconds) were recorded on each trial. Means and standard deviations were calculated for each item and condition. To eliminate outliers, a cutoff of 2 SDs above or below each participant's mean RT was used, and values outside these cutoffs were removed. Accuracy and RT data were analyzed using logistic and linear regression, respectively, with mixed-effects: fixed effects for verb categories, and random by-participant and by-item intercepts. In order to test the relative explanatory value of the lemma frequency and morphological family size measures calculated according to the Single and Dual Entry accounts, different regression models were constructed for the two accounts, with responses to the two ambiguous verb categories as independent factor. The Single Entry model included verb category, semantic relatedness, and lemma frequency (as calculated according to the Single Entry account) and the Dual Entry model included semantic relatedness and lemma frequency (as calculated according to the Dual Entry account). Morphological family size was not included as it did not contribute to the variance explained by the models. The dual entry model did not include verb category, as according to this account polysemous and homonymic verbs do not differ categorically, but only in the degree of semantic relatedness

between their two readings. Regression was performed using the lme4 package running in R program (<http://www.r-project.org>).

2.6.2. fMRI data pre-processing and analysis—Neuroimaging data processing and statistical analyses were performed using the Statistical Parametric Mapping (SPM8) software (<http://www.fil.ion.ucl.ac.uk/spm>). The data were pre-processed through the web-based Northwestern University Neuroimaging Data Archive (<https://nunda.northwestern.edu>) with the following steps: (a) slice-timing correction was not done due to the short TR and the multiband acceleration, (b) motion correction of functional images, (c) regressed frame displacement, as well as CSF and white matter signal using CompCor (Behzadi, Restom, Liao, & Liu, 2007), (d) a highpass filter was applied to the functional data with a cutoff of 0.01 Hz to remove signal drift, (e) linear coregistration of functional and anatomic image in native space using boundary-based registration (Greve & Fischl, 2009), (f) non-linear transformation of the anatomic image into the standard MNI space using VBM8 toolbox and DARTEL (Ashburner & Friston, 2000), and (g) 6 mm smoothing.

In the first level of analysis, conditions were modeled separately for each verb category and the baseline measure (letters) using a general linear model (GLM; Friston et al., 1995). In the final model, lemma frequency, morphological family size, and semantic relatedness under the dual account for experimental stimuli were incorporated as parametric modulators for the experimental conditions, to eliminate variability within conditions arising from these dimensions of the stimuli. The fMRI analyses included four primary contrasts, examining: (1) lexical effects (all verbs versus letters), (2) the ambiguity effect (ambiguous > unambiguous), (3) lexical selection effects (homonymic > unambiguous; homonymic > polysemic), and (4) grammatical computation effects (polysemic > unambiguous; polysemic > homonymic).²

Individual participants' summary activation maps for the contrasts of interest were entered into a second level analysis (i.e., random effects analysis) to enable inferences at the group level. Following this second-level analysis, statistical parametric maps were generated, displaying a t-statistic at each voxel (SPM {t}) that characterizes differences in activation for any condition. Second-level statistics were evaluated using cluster-extent thresholding based on an estimate of image smoothness in AFNI with updated AFNI 3DClusSim function (Cox, 1996), following the evidence of a disproportionately high rate of false positive results yielded by family-wise (FWE) cluster-level correction in SPM (Eklund, Nichols, & Knutsson, 2016). Cluster extent thresholds were determined to give a whole brain corrected p-value of 0.05. If a significant cluster of activation was not seen using a p-value of 0.001 uncorrected, a lower p-value (0.05) and a higher cluster minimum (based on 3DClusSim) were obtained in order to maintain an overall alpha < 0.05 corrected. The two regions of significant activation found to be involved in the processing of ambiguity, the left inferior frontal and parietal regions, were further explored using a region-of-interest (ROI) time-

²We also tested the contrast of unambiguous verbs versus unambiguous nouns and unambiguous nouns versus letters which allowed observation of regions involved in noun and verb processing independently. As these contrasts constituted posthoc analyses and are of less theoretical significance, we report these findings in the supplementary material.

course approach. This involved extraction of the whole timeseries for each ROI, trial averaged, and converted to percent signal change. To do this, we obtained the mean signal change of the BOLD signal for each verb condition across subjects, sessions and trials in the two seconds proceeding and 12 s following the onset of the condition.

3. Results

3.1. Behavioral data

Accuracy and RT means and standard deviations for each condition are summarized in Table 3. Fig. 2 illustrates accuracy and RT across conditions. Prior to statistical analysis of RTs, incorrect responses (comprising 12% of the data) and outliers (comprising 0.2% of the data) were removed. Participants were highly accurate on the task (86% correct). Accuracy for verb category was highest for unambiguous (89% correct) and polysemic verbs (87% correct) and least accurate for homonymic verbs (81% correct). Participants were fastest in responding to unambiguous verbs (797 ± 193 ms), slower for polysemic verbs (835 ± 225 ms), and slowest for homonymic verbs (866 ± 229 ms).

To assess whether accuracy effects could be accounted for better by the Single Entry or Dual Entry account, we compared the Single Entry regression model (including verb category, semantic relatedness, and lemma frequency values as calculated according to the Single Entry account) and the Dual Entry regression model (including the semantic relatedness and lemma frequency values as calculated according to the Dual Entry account). The two models were not statistically different from each other ($\text{Chisq} = 2.808$, $p = .094$). Importantly however, as shown below, the verb category factor was significant in the Single Entry model, suggesting a contribution of verb category above and beyond semantic relatedness. Results of the Single Entry regression analysis indicated that accuracy was significantly predicted by verb category. Participants' responses to homonymic verbs were less accurate than to unambiguous ($z = -4.015$, $p < .000$) and polysemic verbs ($z = -2.135$, $p = .033$). No significant difference in accuracy between unambiguous and polysemic verbs ($z = -1.814$, $p = .069$) was found. Lemma frequency accounted for a significant part of the variance for accuracy ($z = 2.134$, $p = .033$).

For RTs, again we first compared the two models, as specified above. There was no difference between the two models ($\text{Chisq} = 1$, $p = .1$). However, as in the accuracy analysis, verb category remained significant in the Single Entry model, even after accounting for the variability explained by semantic relatedness. This model indicated that participants' responses to homonymic verbs were significantly longer compared to unambiguous ($t = 4.478$, $p < .001$) and polysemic verbs ($t = 2.171$, $p = .034$). Also, responses to polysemic verbs were significantly longer than to unambiguous verbs ($t = 2.258$, $p = .028$). Lemma frequency accounted for a significant part of the variance for RT ($t = -2.030$, $p = .046$), in addition to the fixed effect.

3.2. fMRI data

Statistical analyses were conducted to determine first whether verb trials differed from letter trials (lexical effect), and secondly, whether different verb categories elicited differential

activation patterns (unambiguous vs. polysemic vs. homonymic). For verb category, we examined whether there were regions supporting the overall effect of ambiguity (ambiguous verbs > unambiguous verbs), and whether neural modulation was modified when homonymy was involved (homonymic > unambiguous verbs, homonymic > polysemic verbs) as opposed to when polysemy was involved (polysemic > unambiguous verbs, polysemic > homonymic verbs).

3.2.1. Lexical (verbs vs. letters) effects—The results of the lexical analysis are presented in Table 4 and Fig. 3. The *Verbs* versus *Letters* contrast revealed a cluster of activation in the left inferior frontal gyrus (IFG) (BAs 45/47) and medial frontal gyrus (MFG). In addition, all verbs also elicited peak activity in the right cerebellum. For the *Letters* versus *Verbs* contrast, right inferior parietal lobule (IPL) and occipital/fusiform gyri and left superior temporal gyrus (STG) and precuneus activation was prominent.

3.2.2. Verb category (unambiguous vs. Polysemic vs. homonymic) effects—The results of the verb category analysis are presented in Table 5 and Fig. 4. Testing for the *effect of ambiguity* (ambiguous > unambiguous) resulted in significant left hemisphere clusters in the IFG (BAs 45/47), MFG and IPL. Clusters in the right orbital and IPL emerged in the reverse comparison (unambiguous > ambiguous). Differences were also found for the unambiguous > polysemic verbs and unambiguous > homonymic verbs contrasts in the bilateral orbital, and right MFG, as well as in the bilateral cingulate cortex, the right IPL and MTG for the latter. Fig. 4A further shows the time course of the mean signal change of the BOLD signal in activated frontal and parietal gyri for each verb condition.

Turning to other analyses, the *effect of lexical selection*, namely homonymic > unambiguous and homonymic > polysemic verbs, both comparisons revealed clusters of activation in the left IFG (BAs 45/47), MFG, and in the right IFG. In addition, the former comparison revealed more pronounced activity in the left IPL and inferior temporal/fusiform gyrus (ITG/FG) though homonymic > polysemic activated the same temporal area. Testing the *effect of grammatical word-form computation*, the contrast polysemic > unambiguous verbs generated activations in the left IFG (BA 45) and IPL with a lower threshold (cluster uncorrected). The contrast polysemic > homonymic verbs elicited no activations.

In order to test the relative explanatory value of lemma frequency and morphological family size as computed according to the Single and Dual Entry accounts, general linear models were constructed where the amplitudes of the task design being fit for each event were modulated by the corresponding variable. The resulting four GLMs (lemma frequency and morphological family size by single and dual entry accounts) were then fit to each subject's data, and root mean square residuals of the models were compared within the significant clusters derived from the contrast of Homonymy versus Polysemy (see above). In a series of two-tailed paired t-tests comparing single and dual entry accounts, no differences were found in the residuals for these regions (all p 's > 0.05).

Finally, to test for the effect of semantic relatedness on the outcome of the fMRI analysis, semantic relatedness was included as a nuisance variable in the verb category model, and previous comparisons between verb categories were repeated. No change in significant

clusters was observed, indicating that the results were independent of the effect of semantic relatedness to the extent it could be estimated from the data.

4. Discussion

The present study investigated the neurocognitive mechanisms of word-class ambiguous verb processing using an fMRI grammaticality judgment task to test two competing theories of representation and processing of these verbs. According to the Dual Entry account, verbs like *brush* are stored in the lexicon separately from their phonologically and orthographically corresponding noun, on a par with verbs with multiple unrelated meanings like *bear*. Conversely, the Single Entry account suggests that such verbs share a core representation with their corresponding noun base-form, and are grammatically converted online. To evaluate the predictions of these two approaches we examined both behavioral and neural patterns associated with processing unambiguous verbs (*bake*), polysemic forms with related noun and verb senses (*brush*), and homonymic forms with unrelated noun and verb meanings (*bear*). Overall verb (compared to letter) processing was also tested.

Consistent with previous studies of word processing, verbs elicited greater left frontal and right cerebellar activation as compared to letter processing, which activated left precuneus and right parietal-occipital regions (e.g., Davis, Meunier, & Marslen-Wilson, 2003). Our posthoc analysis (see supplementary material) contrasting unambiguous verbs > unambiguous nouns also implicated the left inferior and medial frontal gyri (IFG and MFG), and the left middle temporal gyrus (MTG). These findings support previous research indicating that the left IFG and MTG are engaged for processing verb-specific information (e.g., phrase structure building, the number of thematic/subcategorization options; Friederici, 2011; Friederici & Kotz, 2003; Malyutina & den Ouden, 2017; Meltzer-Asscher, Schuchard, den Ouden, & Thompson, 2013; also see Thompson & Meltzer-Asscher, 2014). In addition, the left MFG is known to be activated in response to uncertainty in decision-making and appears to be active in a variety of tasks that require semantic/cognitive control, as do ambiguous verbs (Barch, Braver, Sabb, & Noll, 2000; Talati & Hirsch, 2005; Volz, Schubotz, & von Cramon, 2005).

Turning to discussion of our primary findings associated with verb processing, we found significant differences in RT based on verb category: homonymic verbs took the longest time to process; polysemic verbs took less time; and unambiguous verbs took the least amount of time. In addition, responses to homonymic verbs were significantly less accurate compared to unambiguous and polysemic verbs. These performance patterns are in line with previous studies showing that ambiguity between multiple meanings produces a disadvantage, while multiple senses produce faster responses (e.g., Beretta et al., 2005; Rodd et al., 2002; Pykkänen, Llinas, & Murphy, 2006). Previous studies also have found differential processing depending on the type of ambiguity, with advantages (i.e., greater priming effects, faster RT) found for polysemous compared to homonymic words (e.g., Klepousniotou & Baum, 2007; Klepousniotou, 2002).

Together with the findings from the present study, these performance patterns are compatible with both Dual Entry and Single Entry accounts. Both predict greater processing costs for

homonymic verbs (e.g., *bear*), with little or no overlap in meaning between their verb and noun form, compared to polysemic verbs (e.g., *brush*), with strong meaning overlap between the two forms. That is, the semantic distance between meanings for homonymic versus polysemic words influences processing time. The greater the distance, the greater the processing cost. The two accounts, however, differ in how they explain the greater processing cost associated with ambiguous versus unambiguous verbs. The Dual Entry account posits separate lexical entries for the noun and the verb form of ambiguous verbs (both homonyms and polysemic verbs). Thus, when encountered, both forms are automatically activated, creating competition between them and requiring resolution of the competition for lexical selection. Such competition resolution is not inherent in processing unambiguous verbs since they are associated with a single entry only. This property renders processing of unambiguous verbs computationally less expensive than processing ambiguous verbs. Alternatively, the Single Entry account, attributes the increased processing cost for ambiguous verbs (for polysemic verbs only) to grammatical word-form processes involved in conversion of words from one class to another. In the case of polysemic verbs, with a noun base-form, this process converts the noun form to the verb form. In addition, in the present study, noun-based, polysemic verbs were presented together with “to” (i.e., “to *brush*”) for grammaticality judgment, creating a mismatch between the prediction of an upcoming verb generated by the infinitive “to” and presentation of a noun-based verb form, resulting in lexical reanalysis. Notably, homonyms do not undergo grammatical word-form processes, yet processing of homonyms required greater RT than processing polysemic verbs, indicating that grammatical word-form processes are less costly than semantic competition between unrelated meanings.

Patterns similar to those noted for the RT data were also noted in the neuroimaging data. Using whole-brain analyses, we observed activation for the contrast *ambiguous verbs* > *unambiguous verbs* (of both types) in the left frontoparietal semantic control network, comprised of the left IFG (BAs 45/47), MFG and inferior parietal lobule (IPL). This result is consistent with previous functional neuroimaging studies of lexical ambiguity, which highlight the role these fronto-parietal regions play in ambiguity resolution, when multiple candidates are activated for selection (e.g., Binder et al., 2009; Boylan, Trueswell, & Thompson-Schill, 2015; Boylan et al., 2015; Eddington & Tokowicz, 2015; Rodd, Longe, Randall, & Tyler, 2010; Seghier, 2013; Xu et al., 2017; Williams, Reddigari, & Pykkänen, 2017). The activity within the MFG and IPL has been associated with high-level executive function and decision-related processes (Talati & Hirsch, 2005; Volz et al., 2005).

Notably, we found similar activation within the network for semantic control for the contrast *homonymic verbs* > *unambiguous verbs*, including the left (and right) IFG (BA 45/47), the IPL, and MFG, whereas, the opposite contrast of *polysemic verbs* > *unambiguous verbs* showed activation only within the left IFG (BA 45) and IPL (cluster-uncorrected), indicating greater reliance on this network for selection of ambiguous words with distant semantic competitors. Further, when we directly contrasted *homonymic verbs* > *polysemic verbs*, activation was found in the left IFG (i.e., BA 44/45/47), MFG, and ITG, as well as the right IFG (BA 47), whereas *polysemic verbs* > *homonymic verbs* showed no regions of significant activation that survived cluster-correction. These results persisted even after accounting for

the degree of semantic relatedness. This supports the hypothesis that all ambiguous verbs are not represented and/or processed in the same manner.

These findings suggest that homonymic verbs, which entail high semantic control and storage demands, activate ventral stream regions, posteriorly (i.e., the ITL) to facilitate access to their semantically distant representations and anteriorly (i.e., the IFG; see Lau et al., 2008) for inhibition of the competing representation and selection of the correct one. The ITL activation reflects demands on semantic storage/access imposed by homonyms, which have two representations, as compared to unambiguous or polysemic verbs, which have only one (as suggested previously by Whitney et al., 2011). In the case of *polysemic verbs* > *unambiguous verbs*, we propose that the left posterior IFG activation reflects the cost of grammatical word formation. However, the null results for the *polysemic verbs* > *homonymic verbs* contrast suggest that grammatical word-formation processes may be relatively less taxing compared to lexical selection, thus not leading (at least with the current task) to a measurable neural cost.

These neural patterns are more compatible with the Single Entry account as compared to the Dual Entry account. The Dual Entry account posits that homonymic and polysemic verbs are similarly taxing, in that semantic competition is inherent in both forms, but because competition is greater in the former and lesser in the latter, it follows that neural activations for *homonymic verbs* > *unambiguous verbs* should be greater than, but overlapping with regions engaged, for *polysemic verbs* > *unambiguous verbs*. Contrary to this prediction, although overall activation was greater for *homonymic* > *unambiguous verbs* as compared to *polysemic verbs* > *unambiguous verbs*, the brain regions implicated in the two contrast were not completely overlapping. Although similar activation within the left posterior IFG (BA 45) and IPL was observed for both ambiguous verb categories, greater neural activity was observed for the homonymic compared to the polysemic verbs in additional fronto-temporal regions. These findings support the Single Entry account and suggest that the greater, but overlapping, activation for *homonymic* > *unambiguous verbs* reflects semantic competition, whereas the greater but nonoverlapping activation found for *polysemic* > *unambiguous verbs* reflects *grammatical computation*. The fact that the polysemic verbs did not activate the left anterior IFG (BA 47), MFG and ITG when compared to unambiguous verbs not only indicates that such semantic competition and selection processes are not at work during the processing of these verbs, but also that these verbs do not differ with respect to storage and lexical access (also see a recent study by Gaston & Marantz, 2017 for MEG data supporting a Single Entry).

Interestingly, these results are inconsistent with those reported by Pliatsikas et al. (2014). Whereas Pliatsikas et al. found increased brain activity within the left IFG (BAs 44/45) for derived words like *brushing*, the present study showed that homonymic verbs (i.e., non-derived forms) activated frontal areas of the brain to a greater extent than polysemic (derived) verbs. However, as discussed above (see Introduction), the tests used to categorize polysemic verbs differed across studies. Unlike the linguistic tests used to classify noun-derived verbs (Myers's Root Suffixation 1984; Clark & Clark, 1979 test) in the present study, the rating questionnaire used by Pliatsikas et al. did not distinguish the directionality of derivation. Thus, it is possible that the increased activity within the left IFG in Pliatsikas

et al. (2014) reflected lexical selection between the two activated stems, rather than or in addition to derivation.

Overall, the present data contribute to our understanding of the neurocognitive mechanisms associated with category ambiguity and grammatical word-formation, a very common, but little studied, phenomenon in natural language. Despite the extensive literature on processing words with multiple unrelated meanings (e.g., homonymous words like bank), vs. words with a single meaning, and words with multiple, related senses (e.g., polysemous words like chicken) vs. those with fewer senses, polysemous noun-verb forms have received little direct attention. Understanding the processing mechanisms associated with words with multiple unrelated and related readings in the mental lexicon can have direct implications for people suffering from stroke-induced word class deficits, which are commonly observed. For instance, defining the neural correlates of different type of verbs in healthy participants will help to inform lesion-deficit patterns associated with brain damage, as well as approaches to intervention for patients with verb deficits. Moreover, future studies can take advantage of homonymic and polysemic words to directly test different theories of lexical processing, such as the coarse vs. fine semantic coding deficit hypothesis (Beeman, 2008) and/or the suppression deficit hypothesis (Tompkins & Lehman, 1998) in patients with both left and right hemisphere damage (see Klepousniotou, Gracco, & Pike, 2014 for discussion of these and other theories).

5. Conclusion

This study demonstrated greater activation for verbs (compared to letters or nouns) in left frontal areas, as found in other studies of verb processing. Moreover, using a well-controlled set of verbs related in meaning to nouns, verbs unrelated in meaning to nouns, and verbs with only a single meaning, the results showed behavioral and neural processing costs for verbs with multiple meanings versus those with single meaning in a fronto-parietal network. Further, processing verbs with multiple unrelated meanings (homonymic verbs) was more computationally expensive than processing those with multiple related senses (polysemic verbs). The processing difference between homonymic and polysemic verbs may be explained in terms of the structure of their lexical representations: in the former there are two separate lexical representations, which are co-activated and compete for selection, whereas in the latter, the different senses of polysemous words not mutually exclusive and may share a core representation.

Acknowledgments

This work was supported by Graduate Research Ignition Grant from the School of Communication and Graduate Research Grant, Northwestern University (awarded to S. Lukic) and in part by the National Institutes of Health grants RO1-DC01948/P50DC012283 (awarded to C. K. Thompson). The authors are very grateful to Dr. Elena Barbieri, Dr. Yu Fen Chen and Azmi Banibaker for their assistance with fMRI data collection, Dr. Ajay Shashikumar Kurani for his help with the fMRI data analysis, and Dr. Masaya Yoshida for valuable discussions.

Appendix

Appendix A

Experimental, Baseline, and Filler Stimuli

	Verb condition (verb pairs)				Baseline condition (letter pairs)				Fillers (noun pairs)			
	Unambiguous verbs	Polysemic verbs	Homonymic verbs	Mismatch verbs	Match letters	Mismatch letters	Match nouns	Mismatch nouns				
1	to adopt	to brush	to bear	the build	aa aaaa	ll aaaa	the barn	to apple				
2	to bake	to buckle	to boil	the deliver	bb bbbb	ff bbbb	the bell	to belt				
3	to buy	to comb	to bug	the destroy	bb bbbbbb	tt bbbbbb	the bone	to blouse				
4	to cancel	to cover	to cast	the detect	cc cccc	ll cccc	the bucket	to carrot				
5	to carry	to crack	to check	the discuss	cc cccccc	ww cccccc	the candle	to celery				
6	to carve	to dress	to clutch	the follow	dd dddddd	gg dddddd	the car	to corn				
7	to clean	to drill	to duck	the grab	ee eee	rr eee	the desk	to deer				
8	to crave	to filter	to fare	the inspect	ff fff	mm fff	the fork	to frog				
9	to delete	to frame	to figure	the learn	gg ggggg	ss ggggg	the scarf	to glove				
10	to detect	to hook	to fly	the observe	hh hhhh	cc hhhh	the guitar	to grape				
11	to donate	to label	to groom	the promote	ii iiiiii	aa iiiiii	the helmet	to horse				
12	to cat	to land	to peer	the propose	ll lllll	ss llll	the kite	to jacket				
13	to erase	to load	to place	the propose	ll llll	bb lllll	the lamp	to lemon				
14	to hire	to lock	to ring	the pull	mm mmmm	cc mmmm	the lid	to mouse				
15	to imitate	to mark	to root	the pursue	pp pppp	ee pppp	the pillow	to peach				
16	to invent	to pump	to sink	the save	rr rrrrr	pp rrrrr	the stapler	to purse				
17	to locate	to rake	to slip	the serve	ss Sss	bb sss	the statue	to sandal				
18	to pour	to stamp	to stem	the sing	ss sssss	tt sssss	the sword	to shark				
19	to resist	to store	to stick	the stir	tt tttt	ii tttt	the tent	to shirt				
20	to sew	to switch	to train	the teach	tt tttt	dd tttt	the tray	to squirrel				
21	to wipe	to test	to watch	the throw	ww wwww	hh wwww	the wallet	to zebra				

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Fig. 1.
Schematic of verb (left) and letter (right) trials in the grammaticality judgment task.

Fig. 2.

Mean response time across the three verb conditions (right) (** $p < .001$, ** $p < .01$). Bars indicate ± 1 standard error of the mean.

Fig. 3.

Activation maps showing activation for the lexical effect: verbs over letters in the left inferior frontal lobe (red), and letters over verbs in the right parietal and occipital areas (blue). The presented map is thresholded at $p < .05$, FWER corrected using cluster-extent based thresholding ($k > 65$) with primary threshold of $p < .001$.

Fig. 4. Activation maps showing activation for: (A) *the ambiguity effect* (ambiguous over unambiguous verbs) in the left frontal and parietal areas and the time course of the mean % BOLD signal change in these areas for the three verb conditions, (B) *the verb category effect* (homonymic over unambiguous and polysemic verbs) in the left inferior frontal and temporal areas. The presented maps are thresholded at $p < .05$ FWER corrected, using cluster-extent based thresholding ($k > 70$) with primary threshold of $p < .001$.

Summary of behavioral and neural predictions and lexical statistics for the three verb categories per different representational theories.

Table 1

Representational hypothesis	Lexical statistics		Process	Predictions	
	Form (surface) frequency	Lemma (root) frequency		Behavioral	Neural
Single Entry	Unamb (bake)	Frequency of V form	Verb is retrieved	High accuracy, fast responses	
	Polysemy (brush)	Frequency of V + N forms	Noun is retrieved, verb is derived from noun Lemma (root) frequency facilitation effect	Lower accuracy, slower responses than unamb	Polysemy > Unamb/Homonymy pIFG (BA 44/45): grammatical (conversion/derivation) process
	Homonymy (bear)	Frequency of V + N forms	Both Verb and Noun form retrieved, strong competition	Lower accuracy, slower responses than unamb (no prediction with respect to polysemy)	Homonymy > Unamb/Polysemy aIFG (BA 47): semantic control pIFG (BA 44/45): semantic selection ITG: lexical representation/activation
Dual Entry	Unamb (bake)	Frequency of V form	Verb is retrieved	High accuracy, fast responses	
	Polysemy (brush)	Frequency of V + N forms	Both Verb and Noun form retrieved, some competition (Verb and Noun form are semantically related)	Lower accuracy, slower responses than unamb	Polysemy > Unamb aIFG (BA 47): semantic control pIFG (BA 44/45): semantic selection ITG: lexical representation/activation
	Homonymy (bear)	Frequency of V + N forms	Both Verb and Noun form retrieved, strong competition (Verb and Noun form are semantically unrelated)	Lowest accuracy, slowest responses	Homonymy > Unamb/Polysemy aIFG (BA 47): semantic control pIFG (BA 44/45): semantic selection ITG: lexical representation/activation

Table 2

Lexical statistics across conditions

	Length		Log Lemma Frequency		Log Word-form Frequency		Morphological Family Size		Imageability	
	Mean (SD)	T-test Statistics	Mean (SD)	T-test Statistics	Mean (SD)	T-test Statistics	Mean (SD)	T-test Statistics	Mean (SD)	T-test Statistics
<i>unambiguous verbs</i>	4.9 (1.2)	<i>Unamb vs Polysemic</i> : $t = 0.80$, $p = .429$	4.23 (0.46)	<i>Unamb vs Polysemic</i> : $t = -1.54$, $p = .130$	3.79 (0.51)	<i>Unamb vs Polysemic</i> : $t = -2.29$, $p = .027$	7.2 (3.7)	<i>Unamb vs Polysemic</i> : $t = 0.31$, $p = .761$	4.9 (1.04)	<i>Unamb vs Polysemic</i> : $t = 1.84$, $p = .073$
<i>polysemic verbs</i>	4.7 (0.7)	<i>Polysemic vs Homonymic</i> : $t = 1.42$, $p = .164$	4.45 (0.46)	<i>Polysemic vs Homonymic</i> : $t = 1.29$, $p = .203$	4.15 (0.52)	<i>Polysemic vs Homonymic</i> : $t = -0.71$, $p = .481$	6.9 (3.3)	<i>Polysemic vs Homonymic</i> : $t = 0.29$, $p = .768$	5.4 (0.66)	<i>Polysemic vs Homonymic</i> : $t = 1.97$, $p = .056$
<i>homonymic verbs</i>	4.4 (0.8)	<i>Unamb vs Homonymic</i> : $t = 1.85$, $p = .072$	4.25 (0.52)	<i>Unamb vs Homonymic</i> : $t = -0.16$, $p = .871$	4.27 (0.50)	<i>Unamb vs Homonymic</i> : $t = 3.04$, $p = .004$	6.6 (3.9)	<i>Unamb vs Homonymic</i> : $t = 0.56$, $p = .577$	4.8 (1.21)	<i>Unamb vs Homonymic</i> : $t = 0.27$, $p = .786$

Table 3

Mean and standard deviation of response time and accuracy across conditions.

	Response Time (ms)		Accuracy	
	Mean	SD	Mean	SD
Conditions				
<i>unambiguous verbs</i>	797	197	0.89	0.31
<i>polysemic verbs</i>	835	234	0.87	0.34
<i>homonymic verbs</i>	866	224	0.81	0.39

Table 4

Peak areas of differential activation for verbs and letters. Results are presented at a threshold of $p < .05$ corrected, based on $p < .001$ voxel-level threshold and a minimum cluster size (65 voxels) determined by an estimate of image smoothness. Regions labeled using the Anatomy Toolbox atlas. MNI = Montreal Neurological Institute; left (L) and right (R) hemispheres; k = number of voxels in cluster; Op = Opercularis; Tri = Triangularis; Orb = Orbitalis.

Contrast Name		MNI Coordinates				
	Region Label	k	t-value	x	y	z
<i>Verbs > Letters</i>	L Inferior Frontal Gyrus (parsTri, parsOrb)	1195	6.35	-50	26	14
	L Posterior-Medial Frontal	167	6.28	-4	16	52
	R Cerebellum	140	6.27	10	-78	-32
	L Precentral Gyrus	72	5.66	-48	0	44
<i>Letters > Verbs</i>	R Fusiform Gyrus	1004	-6.65	38	-74	-14
	L Precuneus	181	-6.36	-4	-68	58
	R Middle Occipital Gyrus	387	-5.75	38	-80	28
	R Postcentral Gyrus	220	-5.39	44	-34	46
	R Supramarginal Gyrus	84	-4.86	54	-46	32

Table 5

Peak areas of differential activation for contrasts of interests. Results presented at a threshold of $p < .05$ corrected, based on $p < .001$ and $\hat{v}_{\text{uncorr}} < 0.001$ voxel-level threshold, minimum cluster size (70 voxels) determined by an estimate of image smoothness. Regions labeled using the Anatomy Toolbox atlas. MNI = Montreal Neurological Institute; left (L) and right (R) hemispheres; k = number of voxels in cluster; Op = Opercularis; Tri = Triangularis; Orb = Orbitalis.

Contrast Name	Region Label	k	t-value	MNI Coordinates		
				x	y	z
<i>Ambiguous > Unambiguous verbs</i>	L Inferior Parietal Gyms (BA40/39)	159	8.29	-36	-52	44
	L Superior Medial Gyrus	288	6.11	-6	22	48
	L Inferior Frontal Gyrus (parsTri)	515	5.85	-40	28	18
<i>Unambiguous > Ambiguous verbs</i>	R Mid Orbital Gyri	106	-6.02	6	38	-8
	R Inferior Parietal Gyrus (BA 40)	224	-5.97	58	-34	30
<i>Homonymic > Unambiguous verbs</i>	L Inferior Frontal Gyrus (parsTri, parsOrb)	1301	6.88	-52	32	18
	L Superior-posterior Medial Gyrus	570	6.83	-6	22	50
	R Inferior Frontal Gyrus (parsTri, parsOper)	223	6.07	52	34	22
	L Inferior Temporal Gyrus	91	6.06	-48	-52	-16
<i>Unambiguous > Homonymic verbs</i>	L Inferior Parietal Gyrus (BA40/39)	149	5.83	-34	-54	44
	R/L Mid Orbital Gyrus	608	-8.33	4	20	-8
	R/L Cingulate Cortex	874	-7.61	8	-44	40
	R Inferior Parietal Gyrus (BA 40)	581	-7.14	58	-42	34
	R Middle Temporal Gyrus	100	-5.98	58	-10	-12
	R Middle Frontal Gyrus	251	-5.76	24	28	36
	R Inferior Frontal Gyrus (parsOrb)	124	7.61	32	26	-6
<i>Homonymic > Polysemic verbs</i>	L Inferior Frontal Gyrus (parsTri)	283	6.25	-36	4	30
	L Inferior Frontal Gyrus (parsOrb)	331	5.84	-50	24	-2
	L Superior-posterior Medial Gyrus	183	5.61	-2	30	54
	L Inferior Temporal Gyrus	70	5.54	-46	-50	-20
<i>Polysemic > Homonymic verbs</i>	None					
<i>Polysemic > Unambiguous verbs</i>	L Inferior Frontal Gyrus (parsTri)	116	5.47	-38	22	24
	^ L Inferior Parietal Gyrus (BA40/39)	67	5.43	-36	-52	46
<i>Unambiguous > Polysemic verbs</i>	R/L Mid Orbital Gyrus	438	-7.12	10	38	-6

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Contrast Name	MNI Coordinates				Region Label
	k	t-value	x	y	Z
	130	-6.64	28	28	42