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How the brain processes different dimensions of argument structure complexity: Evidence from fMRI

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ABSTRACT

Verbs are central to sentence processing, as they encode argument structure (AS) information, i.e., information about the syntax and interpretation of the phrases accompanying them. The behavioral and neural correlates of AS processing have primarily been investigated in sentence-level tasks, requiring both verb processing and verb-argument integration. In the current functional magnetic resonance imaging (fMRI) study, we investigated AS processing using a lexical decision task requiring only verb processing. We examined three aspects of AS complexity: number of thematic roles, number of thematic options, and mapping (non)canonicity (unaccusative vs. unergative and transitive verbs). Increased number of thematic roles elicited greater activation in the left posterior perisylvian regions claimed to support access to stored AS representations. However, the number of thematic options had no neural effects. Further, unaccusative verbs elicited longer response times and increased activation in the left inferior frontal gyrus, reflecting the processing cost of unaccusative verbs and, more generally, supporting the role of the IFG in noncanonical argument mapping.

1. Introduction

1.1. Dimensions of argument structure complexity

An important aspect of sentence comprehension and production is establishing predicate-argument relations between the sentential predicate, most often a verb, and the phrases accompanying it. Verbs play a central role in sentences, as they determine the number of arguments appearing in the sentence as well as their syntactic category (e.g., noun phrase vs. prepositional phrase), semantic role (e.g., Agent (volitional cause of an event) vs. Theme (undergoer of an event)) and structural position (i.e., whether they are mapped to object or subject position). Collectively, this information is referred to as 'argument structure' information, and is sometimes represented as a 'thematic grid', consisting of so-called thematic roles specifying the arguments selected by the verb, e.g. Agent, Theme, Goal, etc.

Verbs differ from one another along several dimensions of argument structure complexity. First, verbs are different with regard to the number of thematic roles they assign, hence the number of arguments associated with them. For example, whereas *wink* is an intransitive ('1-place') verb, i.e., it has only one thematic role (1a), *cut* is transitive ('2-place'), meaning it is associated with two arguments (1b). Thus, the lexical representation of *cut* (2b) is more complex than that of *wink* (2a).

(1)	a. John winked.
	b. John cut the bread.
(2)	a. *wink* [$_\theta$ Agent]
	b. *cut* [$_\theta$ Agent, $_\theta$ Theme]

In addition, some verbs have multiple thematic realization options, and can be used either transitively or intransitively. For example, so-called 'alternating transitivity' verbs like *break* have transitive and intransitive alternates (3), whereas nonalternating verbs like *cut* can only be used transitively (4). In terms of lexical representations, it is an open question whether *break* is more complex than *cut*. One possibility is that *break* has two distinct but related lexical entries (5), rendering it more complex than *cut*. This view is supported by the observation that in some languages (e.g.,

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Hebrew, Japanese), the transitive and intransitive forms of verbs like *break* are morphologically distinct. Alternatively, *break* may have a single lexical entry with a single thematic grid (either transitive or intransitive), with the other use derived online via a lexical or grammatical operation (see. e.g. Chierchia, 2004; Hale & Keyser, 1986; Levin & Rappaport Hovav, 1995; Reinhart, 2002).

(3)	a. John broke the vase.
	b. The vase broke.
(4)	a. John cut the bread.
	b. ∗The bread cut.
(5)	*break* [$_{\theta}$ Cause, $_{\theta}$ Theme], *break* [$_{\theta}$ Theme]

The intransitive use of *break* highlights another important dimension of argument structure complexity. Intransitive verbs can be split into two classes: unergatives and unaccusatives (Perlmutter, 1978). Unergative verbs select for an Agent argument, the causer of the event denoted by the verb. In (6a), it was John who caused the winking. In contrast, unaccusative verbs assign the role of Theme to their single argument. Themes, unlike Agents, passively undergo a change. For example, in (6b), John, himself, did not cause the falling. Rather, some other entity caused John to fall (e.g., a slick sidewalk). Interestingly, the argument structure properties of these intransitive forms render sentences with unaccusative verbs more complex than those with unergative verbs. In sentences with unaccusatives, the Theme argument surfaces in the sentential subject position, deviating from the tendency for canonical mapping of Agent arguments to the subject position, as in unergatives. In spite of these distinctions, unaccusative and unergative verbs entail equally simple thematic grids: both encode a single thematic role (compare (7) to (2a)).

(6)	a. John winked.
	b. John fell.
(7)	*fall* [$_{\theta}$ Theme]

1.2. Processing of argument structure at the sentence level

Several studies have investigated the psycholinguistic and neural correlates of the different aspects of argument structure complexity discussed above (see Thompson & Meltzer-Asscher, 2014, for a review). Neuroimaging studies with cognitively healthy participants have found differential activation patterns based on the number of thematic roles in sentence contexts, although these patterns vary across studies. Ben-Shachar, Hendler, Kahn, Ben-Bashat, and Grodzinsky (2003) found increased bilateral superior temporal sulcus (STS) activation as the number of arguments in the sentence increased, suggesting that these regions are critical aspects of the neural network for verb and verb argument structure processing in sentences. In contrast, Shetreet, Palti, Friedmann, and Hadar (2007) found that the right anterior cingulate and medial precuneus were sensitive to the number of arguments, indicating that these regions also may be part of the neural circuitry for verb argument structure processing.

With regard to the processing of verbs with multiple thematic options, Shetreet, Palti, Friedmann, and Hadar (2007) and Shetreet, Friedmann, and Hadar (2010b) conducted an fMRI studies with verbs that select for different types of arguments (e.g. *finish*, which selects for either an NP or a clause), as opposed to verbs that allow only one thematic option (e.g. *light*, which selects for only for an NP). Comparing these two verb types, the authors found a left hemisphere network, including the left STG (Brodmann Areas [BAs] 40/22/39) as well as the inferior (BA 47) and middle frontal gyri (MFG, BA 9), for processing verbs with more compared to fewer thematic options. This finding is in line with early cross-modal priming experiments reported by Shapiro, Zurif, and Grimshaw (1987), demonstrating that the processing cost of verbs in sentence contexts increases with the number of thematic realization options. However, Shetreet, Friedmann, and Hadar (2010b), in an fMRI sentence comprehension study of verbs with optional arguments (e.g., *eat*) in Hebrew, found no differential activation associated with optional-argument verbs as opposed to verbs with one thematic option, when realized with the same number of arguments.

Turning to the processing of unaccusativity, a number of studies have shown that unaccusativity poses a problem for aphasic speakers, particularly those with agrammatic aphasia. Specifically, these speakers tend to produce fewer sentences with unaccusative verbs than controls (Kegl, 1995; Thompson, 2003), and produce such sentences less accurately (Bastiaanse & van Zonneveld, 2005; Lee & Thompson, 2004; McAllister, Bachrach, Waters, Michaud, & Caplan, 2009; Stavrakaki, Alexiadou, Kambanaros, Bostantjopolou, & Katsarou, 2011). Additionally, there is considerable behavioral evidence that sentences with unaccusative verbs are processed differently in healthy individuals than those with unergative verbs (Bever & Sanz, 1997; Burkhardt, Pinango, & Wong, 2003; Friedmann, Taranto, Shapiro, & Swinney, 2008; Koring, Mak, & Reuland, 2012; Lee & Thompson, 2011; Moed, Kuperman, & Kučerová, 2013). Moreover, it has been claimed that unaccusative structures are acquired later than unergative ones, in both first and second-language acquisition (e.g. Babyonyshev, Ganger, Pesetsky, & Wexler, 2001; Borer & Wexler, 1987; Oshita, 2001). In a neuroimaging study, Shetreet, Friedmann, and Hadar (2010a) compared brain activation during comprehension of sentences with nonalternating unaccusative, unergative and transitive verbs in Hebrew. Differential activations in response to unaccusative sentences again revealed a left hemisphere network, engaging both the left inferior frontal gyrus (IFG, in BAs 45 and 46), and the left posterior middle temporal gyrus (MTG). Left inferior frontal and posterior temporal networks also have been argued to support processing of other noncanonical structures such as passive sentences, which resemble sentences with unaccusatives in that the Theme argument surfaces in subject position (Hirotani, Makuuchi, Ruschemeyer, & Friederici, 2011; Mack, Meltzer-Asscher, Barbieri, & Thompson, 2013; Yokoyama et al., 2007).

1.3. Argument structure information in single word processing

Whereas the studies mentioned above add to our knowledge of how verbs are processed in sentences, they leave some questions unanswered. In particular, is argument structure information processed even when verbs are encountered in citation form, rather than in sentence contexts? For example, brain activation associated with sentences with more as opposed to fewer verb arguments may reflect either processing the more complex lexical representation of the verb or increased verb-argument integration demands. Similarly, activation in response to sentences with unaccusative as opposed to unergative verbs might reflect either a lexical difference between the two verb types, or a difference at the sentence level (e.g. the occurrence of a Theme argument in subject position in the former, but not in the latter).

In theoretical linguistics, there is an ongoing debate over whether or not argument structure information is encoded in lexical representations at all. Radical constructivist approaches (e.g. Borer, 2005) hold that lexical roots are not associated with any syntactically-relevant information, argument structure included. In contrast, lexicalist approaches (e.g. Horvath & Siloni, 2010; Meltzer-Asscher, 2011; Reinhart, 2002) argue that detailed thematic grids must be specified in the lexicon. Other approaches (e.g. Ramchand, 2008) take a middle ground, arguing that argument structure information encoded in the lexicon is minimal. In terms of processing, the fact that argument structure information becomes available instantaneously and, in many cases, is not affected by the sentence form in which the verb appears (e.g. Friedmann et al., 2008; Shapiro et al., 1987) have led many researchers to assume that argument structure information is retrieved and processed as verb lemmas are encountered.

Based on this, it is important to test processing of isolated verbs with different argument structures. Although single-word processing may be considered less natural compared to sentence processing, several studies found differential processing effects even for verbs in citation form, manipulating argument structure, and in particular the number of thematic roles. A prominent finding is that agrammatic speakers perform more poorly on verb naming and reading as the number of thematic roles of the verb increases (Barbieri, Aggujaro, Molteni, & Luzzatti, 2013; Cho-Reyes & Thompson, 2012; Kemmerer & Tranel, 2000; Kim & Thompson, 2000, 2004; Luzzatti et al., 2002; Thompson, Lange, Schneider, & Shapiro, 1997; Thompson, Lukic, King, Mesulam, & Weintraub, 2012). Neuroimaging studies have also shown differential activation patterns associated with processing verbs with different numbers of thematic roles, indicating that posterior perisylvian regions, in particular the angular gyrus (AG) bilaterally, is crucial for processing verbs with more compared to fewer thematic roles (Thompson, Bonakdarpour, & Fix, 2010; Thompson et al., 2007). These findings strongly suggest that argument structure is lexically represented, and processed even when verbs are encountered as singletons outside of sentence contexts.

In contrast to the number of thematic roles, other aspects of argument structure complexity have not been adequately investigated in single verb processing. One previous neuroimaging study examined processing of verbs with multiple thematic options, comparing the neural networks engaged for processing alternating unaccusative (e.g., *break*) and unergative verbs using a visual lexical decision task (Meltzer-Asscher, Schuchard, den Ouden, & Thompson, 2012). Results showed a network for alternating verbs, including the inferior parietal (i.e., significant activation in BAs 39/40) and middle-superior frontal gyri (BAs 8/9), which the authors interpreted as reflecting processing of a greater number of thematic roles and ambiguity associated with alternating verbs, respectively. With regard to unaccusativity, agrammatic speakers have been shown to name unaccusative verbs less accurately than unergative verbs (Kim, 2005; Luzzatti et al., 2002; McAllister et al., 2009; Thompson, 2003), indicating that unaccusatives are relatively difficult to process even in isolation. However, to our knowledge no psycholinguistic or imaging studies examining nonalternating unaccusative verb processing devoid of sentence context have been reported.

1.4. Testing a neurocognitive model of argument structure processing

Thompson and Meltzer-Asscher (2014) proposed a neurocognitive model of argument structure processing at both the word and sentence level, based on the extant literature examining the neural mechanisms of verb processing. The model encompasses three functions: (1) access to stored lexical information (i.e. retrieval of argument structure information from memory), (2) structure building and manipulation, and (3) syntactic–semantic integration of verb and arguments. The authors suggest that argument structure processing engages a widespread, mostly left-lateralized perisylvian network, with access to stored lexical information supported mainly by the AG, bilaterally, syntactic structure building and syntactic manipulation (i.e. movement of constituents to non-canonical positions) supported by the left IFG, which is thus critical for processing noncanonical structures, and sentence-level syntactic and semantic verb-argument integration buttressed by the posterior STG/MTG. This model bears some resemblance to the model for sentence processing proposed in Friederici (2012). Friederici's model includes two ventral streams and two dorsal ones. Most relevant for our purposes are the ventral semantic stream, in which lexical-semantic information retrieved from the MTG is transferred via anterior temporal regions to anterior IFG, and the dorsal route involved in complex syntactic computation (e.g. movement) and verb-argument integration, that connects the posterior IFG to posterior temporal regions.

The current experiment aimed to further test and elaborate our model for argument structure processing by investigating brain activation patterns associated with different dimensions of argument structure complexity using a single task. Since our aim was to focus on lexical information associated with verbs and lexical processing, we used a lexical decision task, shown to be sensitive to differences in argument structure as well as lexical-semantic properties of verbs in other studies (Gennari & Poeppel, 2003; McKoon & Macfarland, 2000, 2002; Thompson et al., 2007, 2010). Specifically, the current experiment examined processing of verbs of different types, including transitive (e.g. *cut*), unergative (e.g. *wink*), nonalternating unaccusative (e.g. *fall*) and alternating unaccusative (e.g. *break*) presented in a minimal syntactic context (i.e., *to V*).

Our first aim was to reinforce our hypothesis with regard to the role of posterior regions in accessing stored lexical information, by investigating the effect of number of thematic roles. To do that, we contrasted transitive verbs with intransitive verbs, with the latter class incorporating both unergatives and unaccusatives. We predicted that this manipulation would yield activation in posterior perisylvian regions of the language network, specifically the angular gyrus, replicating our previous studies (Thompson et al., 2007, 2010).

Next, to further assess the neural basis of processing multiple thematic options, we contrasted alternating unaccusatives, which have two argument realization options, with nonalternating unaccusatives, transitives and unergatives, all exhibiting only one thematic option. If alternating unaccusatives are associated with two lexical entries, whereas the other verb types are associated with only one, then this predicts greater activation for alternating compared to nonalternating verbs in regions of the language network associated with ambiguity resolution, for example, in middle-superior frontal regions as found in other studies (cf. Meltzer-Asscher et al., 2012; Shetreet et al., 2007).

Finally, we wished to study processing associated with isolated unaccusatives, which has not previously been investigated. For this purpose, we examined the contrast between nonalternating unaccusative verbs and both unergative and transitive verbs. We did not include alternating unaccusatives verbs in this contrast because they have an additional, transitive, thematic grid. Because unaccusative verbs entail noncanonical mapping of verb arguments, we predicted that their processing would engage the left IFG, associated with noncanonical sentence processing in our model (see also Friederici, 2012).

2. Methods

2.1. Participants

Twenty nine healthy volunteers participated in the study (18 women): 16 young adults (*M* age = 24, range = 19–38) and 13 older adults (*M* age = 62, range = 54–70). All were right-handed, monolingual English speakers with normal or corrected-to-normal vision and hearing, and no reported history of neurological or speech-language disorders. Participants signed an informed consent prior to scanning, and were paid for their participation. The experiment was approved by the Institutional Review Board at Northwestern University.

2.2. Materials

Stimuli included verbs of four types: unergatives, nonalternating unaccusatives, alternating unaccusatives and transitives. Eighteen verbs of each type were selected. Verbs were initially classified as transitive, intransitive or alternating based on the authors' intuitions. In addition, intransitive verbs were classified as unergative or unaccusative based on Levin and Rappaport Hovav's (1995) identification of verb classes in English. To confirm verb classifications, the first hundred instances of each verb form entered in the Corpus of Contemporary American English (COCA, http://corpus.byu.edu/coca/) were coded for whether they appeared with or without a complement. For unergative and nonalternating unaccusatives, only verbs used intransitively in at least 89% of the cases were included; for transitives, only those used transitively, with a direct object, in at least 88% of the cases were included; alternating unaccusatives were included if usage varied between transitive and intransitive form (i.e., between 11% and 91% of the cases were intransitive). All verbs were able to select animate subjects.

The four verb lists were matched on log frequency of usage as a verb according to COCA (F (3,68) = 1.944, p = .131), number of letters (F (3,68) = .718, p = .545), orthographic neighborhood density (F (3,68) = .32, p = .811), and mean bigram frequency (F (3,68) = .19, p = .903), with the latter two measures retrieved from MCWord (Medler & Binder, 2005).[1] Since many English verbs are homonymous with nouns (e.g. *break*), verbs also were matched for the ratio of noun to verb usage according to COCA, with no significant differences between verb groups (F (3,68) = .443, p = .723). We obtained imageability norms using a questionnaire, asking 20 healthy participants (different from our experimental participants) to rate verbs preceded by *to* (e.g. *to break*) on a 1–7 scale. Results showed that the four verb classes differed on imageability (F (3,68) = 11.259, p < .001). Post-hoc tests (Bonferroni-corrected) revealed that nonalternating unaccusative verbs (M = 4.17, SD = 1.09) and transitive verbs (M = 4.77, SD = 1.17) were significantly less imageable than alternating unaccusatives (M = 5.68, SD = .52) and unergatives (M = 5.81, SD = 1.02). The stimuli, including imageability ratings and percent of intransitive usage, are provided in Appendix A.

Additionally, 48 pseudoverbs (e.g. *to roak, to ventire*) were included in the study, so that word-pseudoword ratio was 3:1 (similar to the ratio in Thompson et al. (2007) and Thompson et al. (2010), which was 4:1). Twenty-four of the pseudoverbs were monosyllabic and 24 bisyllabic. Verbs and pseudoverbs were matched on number of letters (t (118) = .662, p = .509).

2.3. Procedure

Stimuli were presented visually using the E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). All verbs and pseudoverbs were preceded by the infinitive marker *to* to avoid grammatical category ambiguity. Words were presented for 1500 ms, followed by a 500 ms presentation of a dashed line. Jittered null events ranging from 0 to 20 s were interspersed between stimuli. Length and order of null events were optimized using OPTSEQ (http://surfer.nmr.mgh.harvard.edu/optseq/). The experiment included two runs, with each real verb appearing twice, once in each run. Pseudoverbs were not repeated across runs. The total time of each run was 10 min. Participants held a response box in their left hand, and were asked to respond to real verbs by pressing with their index finger, and to pseudoverbs by pressing with their middle finger. Participant responses were acquired with Cedrus RB610 response boxes and recorded by E-Prime.

2.4. Data acquisition and analysis

2.4.1. Behavioral data analysis

Subjects' performance on the lexical decision task was analyzed by means of multiple regression, with reaction time as the dependent variable. Regression was performed using the lme4 package (Bates, Maechler, & Bolker, 2012) running in R (http://www.R-project.org), following the mixed-effects models approach (Baayen, Davidson, & Bates, 2008), with item and participant as random factors. The analysis was performed stepwise, by introducing one predictor (fixed effects) at a time and evaluating its contribution to the explanation of variance by performing ANOVAs between the model containing that predictor and the model without it. Random slopes for significant predictors were also introduced in the analysis and their contribution to the model was evaluated as for fixed effects. Statistical significance was evaluated using Markov Chain Monte Carlo sampling (Baayen et al., 2008). Outliers were identified and excluded following the implementation of the best-fit model, using 2.5 standard deviations of the residual errors as criteria. The final model was then refitted in order to ensure that results were not driven by a few outliers. The main variable of interest was verb type, with four levels (alternating unaccusatives, nonalternating unaccusatives, unergatives and transitives).

In addition to verb type, lexical variables were entered in the model as predictors to account for factors that may influence speed of lexical access and word recognition. These included *word length* (in letters), *word frequency,* and *imageability*. Participant age was also included as a predictor. Continuous variables were centered on their means prior to being entered in the statistical analysis to avoid collinearity. Word length and word frequency have been reported to influence reaction times both in lexical decision and confrontation naming tasks (see Hudson & Bergman, 1985; O'Regan & Jacobs, 1992: but see Frederiksen & Kroll, 1976; Richardson, 1976 for negative evidence on lexical decision), showing inhibitory and facilitatory effects as they increase, respectively. Similarly, imageability has been shown to affect patterns of visual word recognition both in normal and aphasic participants (Marcel & Patterson, 1978; Richardson, 1975); better accuracy and faster reaction times have been reported for highly imageable vs. poorly imageable words.

2.4.2. MRI data acquisition and analysis

Scanning was carried out on a Siemens TIM Trio 3T with a 32-channel head coil. T1-weighted anatomical scans were acquired at the beginning of the protocol (TR = 2300 ms; TE = 2.91 ms; flip angle = 9°; matrix size = 256 × 256; FOV = 256 mm; voxel size = 1 × 1 × 1; 176 slices). Functional volumes with BOLD contrast were obtained with gradient echo-planar imaging sequences (TR = 2000 ms; TE = 30 ms; flip angle = 80°; matrix size = 64 × 64; FOV = 220.16 mm; voxel size = 3.44 × 3.44 × 3; 32 slices).

Preprocessing and statistical analysis of fMRI data were performed using SPM8 (http://www.fil.ion.ucl.ac.uk/spm/software/spm8/). Preprocessing consisted of slice-acquisition timing correction, realignment of the anatomical scans to the mean functional

[1] Recently, de Zubicaray, Arciuli, and McMahon (2013) argued that premotor cortex activation can arise due to ortho-phonological regularities characteristic of verbs (rather than due to action semantics, for instance). Although the verbs from the different classes in our experiment were controlled for orthographic neighborhood density and mean bigram frequency, we cannot rule out at this point the possibility that there exist in English subtle orthographic cues distinguishing the verb types investigated. However, such cues, if they exist, have not been identified yet.

volume, normalization of anatomical and functional scans to the MNI 152-subject template brain, and smoothing using a 9 mm kernel. For first-level analysis, a 128 s high-pass filter was applied. The four verb types, as well as pseudoverbs, were modeled as conditions. Because the four verb classes were not controlled for imageability, imageability was entered as a parametric modulator to each verb type. The six movement parameters from realignment were entered as regressors.

The following contrasts were used to test for effects of argument structure complexity: effect of number of thematic roles: *transitive > nonalternating unaccusative + unergative*; effect of number of thematic options: *alternating unaccusative > transitive + nonalternating unaccusative + unergative*; effect of unaccusativity: *nonalternating unaccusative > transitive + unergative.* In second-level analyses, these effects were tested using one-sample *t*-tests, with participant age entered as a covariate. For the unaccusativity contrast, a further second-level analysis was performed, where in addition to age, a second covariate was introduced, namely the individual difference between the mean RT for nonalternating unaccusative verbs, and the combined mean RT for transitive and unergative verbs (Mean RT unaccusative – ((Mean RT transitive + Mean RT unergative)/2)). Group analyses were thresholded at $p < .05$, corrected for multiple comparisons using the False Discovery Rate (FDR; Benjamini & Hochberg, 1995), with a cluster extent threshold of $k \geqslant 25$ (200 mm^3). Significant clusters of activation were localized using the Automated Anatomical Labeling atlas (AAL; Tzourio-Mazoyer et al., 2002).

In addition, follow-up conjunction analyses were performed to ensure that observed effects were not due to imageability differences between the verb classes. These analyses identified regions that were significantly activated in all relevant pairwise contrasts: number of thematic roles (*transitive > unergative* & *transitive > nonalternating unaccusative*), number of thematic options (*alternating unaccusative > transitive* & *alternating unaccusative > nonalternating unaccusative* & *alternating unaccusative > unergative*), and unaccusativity (*nonalternating unaccusative > unergative* & *nonalternating unaccusative > transitive*). Since the transitive and nonalternating unaccusative classes, as well as the alternating unaccusative and unergative classes, were matched for imageability, there was one pairwise comparison within each conjunction analysis that was matched for imageability. Therefore, any regions significantly activated in the conjunction analyses should be interpreted as effects of verb type. Each pairwise activation map was thresholded at an uncorrected voxel-wise threshold of $p < .005$ and a cluster extent threshold of $k \geqslant 25$ (200 mm^3).

3. Results

3.1. Behavioral results

3.1.1. Accuracy

Mean accuracy was computed for 28 participants, with one excluded due to technical failure of the response box. Participants performed well overall on the task (97.3%), with no major differences between young and older participants (young: 97.5%; older: 97%). Accuracy was above 95% for all verb types (nonalternating unaccusative: 96.9%; alternating unaccusative: 95.3%; transitive: 99.2%; unergative: 97.7%), with similar distributions across the two groups of participants.

3.1.2. Reaction times

Mean reaction times were computed only on correct responses. Participants were slower in responding to pseudoverbs (919 ± 232 ms) than verbs (738 ± 204 ms), as shown by the comparisons between pseudoverbs and each verb class (nonalternating unaccusative, alternating unaccusative, transitive and unergative), all highly significant ($p < .001$).

Reaction times for verbs (excluding pseudoverbs) were log-transformed prior to the regression analysis in order to render a distribution approaching the normal curve. *Verb type* was highly significant in isolation for the comparisons involving nonalternating unaccusatives, which elicited longer RTs as compared to all the other verb types (alternating unaccusatives: $t = -4.93$, $p < .001$; transitives: $t = -4.98$, $p < .001$; unergatives: $t = -3.98$, $p < .001$). The effect of verb type persisted with the introduction of the other predictors, including *imageability*, which was not significant ($t = -0.92$, p = ns) and did not contribute to the model fit. Among the other variables, *word frequency* was highly significant ($t = -8.01$, $p < .001$) and improved the model fit ($\chi^2 = 61.4$, $p < .001$), and so did its random slope ($\chi^2 = 7.8$, $p = .02$). There was no significant interaction between verb type and frequency. *Word length*, when introduced in the model, was not a significant predictor and did not contribute to the model fit. *Age* was a significant predictor in the analysis ($t = 2.48$, $p = .013$) and improved the model fit ($\chi^2 = 5.87$, $p = .015$).

Therefore, the final model included verb type, word frequency (including its random slope) and participant age as predictors. In this model, age and word frequency were highly significant ($t = 2.61$, $p = .009$ and $t = -8.95$, $p < .001$), indicating longer RTs for older participants and for less frequent words. As far as our main predictor of interest, i.e. verb type, the

Table 1
Areas of differential activation for contrasts of argument structure complexity. Peak Montreal Neurological Institute (MNI) coordinates, cluster size (mm^3), maximal *t*-values, and voxel-level *p*-values (FDR-corrected) are reported. *Notes:* LH = left hemisphere; MTG = middle temporal gyrus; IFG = inferior frontal gyrus.

Contrast	Region	Peak coordinates			Cluster size	*t*	*p*
		x	*y*	*z*			
Number of arguments							
Transitive (2) > nonalternating unaccusative + unergative (1)	LH posterior MTG, middle occipital gyrus	−50	−72	10	320	6.53	0.013
Nonalternating unaccusative + unergative (1) > transitive (2)	*None*						
Number of thematic options							
Alternating (2) > transitive + nonalternating unaccusative + unergative (1)	*None*						
Transitive + nonalternating unaccusative + unergative (1) > alternating (2)	*None*						
Mapping canonicity							
Nonalternating unaccusative > transitive + unergative	LH precentral gyrus, IFG (pars opercularis)	−46	2	28	672	6.21	0.022
Nonalternating unaccusative > transitive + unergative with RT difference as covariate	LH precentral gyrus, IFG (pars opercularis)	−46	2	28	384	6.14	0.034
Transitive + unergative > nonalternating unaccusative	*None*						
Participant age (all contrasts)	*None*						

only significant comparisons were those involving nonalternating unaccusatives, which elicited longer RTs as compared to the other verb types (p's < .001).

3.2. fMRI results

The results of the combined contrasts are presented in Table 1 and Fig. 1. The contrast testing effects of number of thematic roles (*transitive* > *unaccusative* + *unergative*) revealed a cluster of activation in the left posterior MTG/middle occipital gyrus. The reverse contrast (*unaccusative* + *unergative* > *transitive*) contained no significant activation. The contrast testing the effect of number of thematic options (*alternating unaccusative* > *transitive* + *nonalternating unaccusative* + *unergative*) revealed no significant activation, and no significant effects were found in the reverse contrast. In the second-level analysis including only age as a covariate, a significant effect of unaccusativity (*nonalternating unaccusative* > *transitive* + *unergative*) was found in the left precentral gyrus and pars opercularis of the IFG. A similar (though smaller) cluster was found for this contrast in the analysis including RT difference as a second covariate. No activation was found in the reverse contrast, in either analysis. No significant effects of participant age as a covariate were found for any contrast, and no significant effect of RT difference as a covariate was found for the unaccusativity contrast.

The results of the conjunction analysis are presented in Table 2. The results mirrored those of the combined contrasts. The conjunction testing for effects of thematic role number (*transitive* > *nonalternating unaccusative & transitive* > *unergative*) resulted in a cluster in the left posterior MTG and middle occipital gyrus. No significant effects were found for the conjunction testing for effects of the number of thematic options (*alternating unaccusative* > *transitive* & *alternating unaccusative* > *nonalternating unaccusative* & *alternating unaccusative* > *unergative*). The conjunction testing for effects of unaccusativity (*nonalternating unaccusative* > *unergative* & *nonalternating unaccusative* > *transitive*) revealed a cluster of activation in the left precentral gyrus and pars opercularis of the IFG.

4. Discussion

In the present study, we examined the neural mechanisms of verb argument structure processing, focusing on three dimensions of complexity: (1) the number of thematic roles, to further elucidate the role of posterior regions in accessing stored lexical information, (2) the number of thematic options, to determine if alternating unaccusatives, which on some accounts are associated with two lexical entries, engage regions of the language network associated with ambiguity resolution, for example, in middle-superior frontal regions, and (3) noncanonical mapping of internal arguments to examine the role of the left IFG in this process.

4.1. Number of thematic roles

With regard to number of thematic roles, we found activation in posterior perisylvian regions. The contrast between 2-place (transitive) and 1-place (nonalternating unaccusative and unergative) verbs elicited MTG and middle occipital lobe activations, largely replicating previous findings of left hemisphere posterior perisylvian activation associated with increased number of thematic roles, both using lexical decision (Thompson et al., 2007, 2010) and verb naming from pictures and videos (den Ouden, Fix, Parrish, & Thompson, 2009). Although the activation peak for this contrast was inferior to the AG, in the posterior MTG in the current study, we propose that the two regions may be functionally similar, involved in representation of lexical-semantic information. In addition, this finding is in line with Friederici (2012), who suggests that the MTG is engaged for retrieval of argument structure information.

Given that there was no significant difference in reaction time between our 2- and 1-place verbs (cf. Thompson et al., 2010), this posterior activation likely reflects linguistic differences between the two verb types. These differences may be due to the increased number of participant roles in transitive vs. intransitive verbs or to some other aspect of semantic complexity associated with a

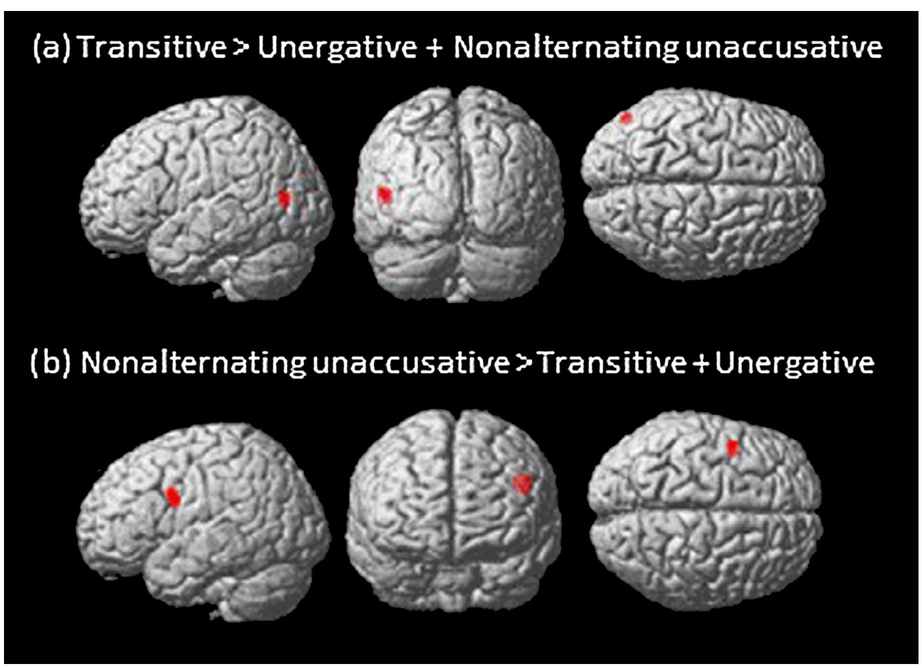


Fig. 1. Regions of differential activation for (a) transitive verbs (2 thematic roles) > unergative and (nonalternating) unaccusative verbs (1 thematic role) (b) (nonalternating) unaccusative verbs > transitive and unergative verbs.

Table 2
Results of conjunction analyses for contrasts of argument structure complexity (each pairwise comparison thresholded at $p < .005$, uncorrected, $k \geqslant 25$). Peak Montreal Neurological Institute (MNI) coordinate and cluster size (mm^3) are reported. *Notes:* LH = left hemisphere.

Contrast	Region	Peak coordinates			Cluster size
		x	*y*	*z*	
Transitive (2) > nonalternaitng unaccusative (1) & transitive (2) > unergative (1)	LH posterior middle temporal gyrus, middle occipital gyrus	−48	−80	4	248
Alternating (2) > transitive (1) & alternating (2) > nonalternating unaccusative (1) & alternating (2) > unergative (1)	*None*				
Nonalternating unaccusative > transitive & nonalternating unaccusative > unergative	LH precentral gyrus, inferior frontal gyrus (pars opercularis)	−44	4	20	1952

transitive action as compared to an intransitive action, e.g. the fact that transitive, but not intransitive actions, involve causation of change in one participant brought about by another participant, and goal-directed action. The results of the present study, as well as those reported in other studies of verb argument structure (Thompson et al., 2007, 2010), suggest that verbs with more complex thematic grids show differential neural activation compared with verbs with less complex grids, even in isolation.

4.2. Number of thematic options

To explore the neural mechanisms associated with processing verbs with multiple thematic options, we contrasted alternating unaccusative verbs, with two thematic options, and the three other verb types, which entail only one thematic option. Contra our hypothesis, this contrast did not yield differential fMRI activation patterns (or response latencies). However, this finding is in keeping with the result of Shetreet et al. (2010b), who also found no differential activation associated with 'optional complement' verbs such as *eat*. Prima facie, this finding may be taken to indicate that alternating verbs such as *break* in English do not have a more complex lexical representation than verbs with one thematic option. For example, it is possible that their lexical representation is similar to that of transitive verbs, e.g.: *break* [$_\theta$ Cause, $_\theta$ Theme], and that the option of not realizing the thematic role of Cause (thus producing the unaccusative version of the verb) stems from a general principle stating that this role can remain unassigned (cf. Reinhart, 2002, who proposes a lexical operation along these lines).

However, this solution poses two problems. First, there are theoretical reasons to think that unaccusative forms are not derived online from transitive entries, but rather that both entries are stored in the lexicon. For example, assuming that phrasal idioms are listed under their lexical head, it is hard to explain the existence of unaccusative idioms, e.g. *burst at the seam* if the unaccusative entry of *burst* is not listed lexically (note that this idiom cannot have a transitive reading, i.e. ∗*burst something at the seam*) (see Horvath & Siloni, 2009, for discussion of similar facts in Hebrew). Moreover, in Meltzer-Asscher et al. (2012) we found activation in bilateral AG and MFG in response to alternating unaccusative compared to unergative verbs. In that study, the posterior activation was argued to reflect processing associated with the greater number of thematic roles associated with the transitive reading of the alternating verbs (as in Thompson et al. (2007, 2010) and the current study), and the frontal activation was interpreted as emerging from the processing of lexical ambiguity, namely the existence of multiple thematic options for the alternating verbs. This interpretation is in line with previous findings showing the region's involvement in processing lexical ambiguity (Chan et al., 2004), as well as with the role this region is assumed to play in working memory and maintenance processes in general (D'esposito, 2001).

The question then arises why, in the current study, we did not replicate the MFG activation from Meltzer-Asscher et al. (2012). Although we do not have a definitive answer to this question, one difference between the previous study and the current one is that in the former, verbs were presented in their bare form, whereas in the latter, they were preceded by the infinitive marker 'to', which may have influenced the way the verbs were processed, rendering them less ambiguous. To test this, we conducted a survey in which 17 participants had to rate, for bare verbs and verbs preceded by 'to' (those which were part of both the 2012 and the current experiment), whether they perceived them as intransitive (rating 1), transitive (5), or somewhere in between (with 3 being 'equally intransitive or transitive'). While the mean ratings were not significantly different between 'to V' and bare V forms ('to V' mean = 2.85, bare V mean = 2.69), the ratings for the 'to V' forms were more dispersed around the mean, reflecting choices of more extreme values. Statistical analysis showed that bare V forms were rated as marginally significantly closer to 3 (that is, more "ambiguous") than 'to V' forms (mean distance from 3 for bare 'V' forms: 1.035; mean distance from 3 for 'to V': 1.32; two-tailed paired-sample $t = 2.092$; $p = .066$), suggesting that 'to V' forms are interpreted as less ambiguous than bare forms.

4.3. Unaccusativity

Turning next to the processing of unaccusativity, we compared activations elicited by nonalternating unaccusative verbs to those elicited by unergative and transitive verbs. Nonalternating unaccusative verbs were associated with a cluster of activation in the left hemisphere precentral gyrus and pars opercularis of the inferior frontal gyrus. Thus, the present results indicate that unaccusative verb processing is associated with distinct neural activation patterns even outside of sentence contexts. In addition, reaction times were longer for nonalternating unaccusative verbs than for the three other verb classes, indicating both behavioral and neural distinctions between these verb types.

In a previous study employing a sentence comprehension task, Shetreet et al. (2010a) also found differential activation in the left IFG for sentences with unaccusative verbs, though the activation was located anteriorly (BA 45/46/47) to the region identified in the present study. The authors interpreted this activation to be associated with syntactic movement or the noncanonical thematic processing required by sentences with unaccusative verbs (see further discussion below).

The left IFG activation observed for the processing of unaccusatives in the present study is in line with the observation that Broca's aphasic speakers, whose lesion often involves inferior frontal regions, have difficulty producing unaccusative verbs (Kim, 2005;

Luzzatti et al., 2002; McAllister et al., 2009; Thompson, 2003). It is also consistent with previous neuroimaging findings indicating that this region supports the processing of passive sentences, in which the Theme argument surfaces in subject position, as in unaccusative sentences (Hirotani et al., 2011; Kinno, Kawamura, Shioda, & Sakai, 2008; Mack et al., 2013; Ye & Zhou, 2009; Yokoyama, Okamoto, et al., 2006; Yokoyama et al., 2007).

An ongoing debate with regard to the processing of noncanonical structures, raised also by the current findings, is whether their increased processing cost (reflected in longer RT and IFG activation) is due to language-specific mechanisms such as syntactic movement (Grodzinsky & Santi, 2008), hierarchical structure building (Friederici, 2011), semantic and/or syntactic integration (Hagoort, 2013) or argument linearization (Bornkessel-Schlesewsky, Schlesewsky, & von Cramon, 2009), or whether it is generated by domain-general mechanisms, such as phonological working memory (Rogalsky, Matchin, & Hickok, 2008), cognitive control (Bornkessel-Schlesewsky & Schlesewsky, 2013; Novick, Trueswell, & Thompson-Schill, 2005) or decision-making (Binder, Liebenthal, Possing, Medler, & Ward, 2004; Venezia, Saberi, Chubb, & Hickok, 2012) (for a recent review, see Rogalsky & Hickok, 2011). Given the nature of our task and experimental stimuli (i.e., lexical decision with single word strings preceded by 'to') hierarchical structure building, semantic/syntactic integration, or phonological working memory are unlikely explanations. Likewise, there is no obvious reason why unaccusative verbs in this experiment would be more difficult in terms of decision-making, as they did not differ from the other verb types in factors known to influence these processes, such as signal-to-noise ratio, response conflict or response bias. Importantly, IFG activation was observed even when covarying out differences in reaction time between nonalternating unaccusatives and the other verb types. Additionally, although age was a significant predictor in the RT analysis, this factor had no significant effect on the fMRI results. These facts strongly suggest that the IFG activation cannot be fully explained by variables related to task demands, but is rather driven by the linguistic nature of the stimuli.

One possible explanation of these findings is that participants may have constructed sentence-level representations that encode the noncanonical mapping of unaccusative structures, i.e., they may have mapped a null (non-overt) Theme to the subject position, a process which on some linguistic accounts involves syntactic movement.[2] This interpretation is not compelling, given that the verbs were presented in citation form. However, if participants did in fact generate sentence-level representations, then our findings are compatible, to some extent, with the claim that the left IFG supports syntactic movement (Santi & Grodzinsky, 2007, 2010) or the linearization of arguments within sentences (Bornkessel-Schlesewsky & Schlesewsky, 2009; Bornkessel-Schlesewsky et al., 2009; Grewe et al., 2005). Still, it is noteworthy that studies which aimed to isolate the cortical effects of syntactic movement (e.g. Rogalsky et al., 2008; Santi & Grodzinsky, 2007, 2010) have found activations in more anterior portions of the IFG, i.e. in pars triangularis, whereas in our study (as well as in several studies investigating passive verb processing, i.e. Hirotani et al., 2011; Mack et al., 2013; Yokoyama, Miyamoto, et al., 2006), peak activation was in the posterior part of the pars opercularis, bordering on premotor cortex.

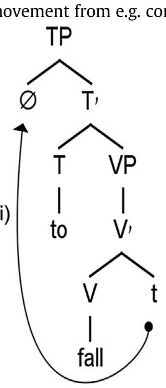
Alternatively, our results may reflect cognitive control operations required to make a lexical decision for an unaccusative verb. Specifically, participants may have had a default expectation for the contents of the verb's thematic grid (i.e., that it contains an Agent) and/or for its argument realization pattern (that an Agent is mapped as the grammatical subject). This expectation may have been overridden upon encountering an unaccusative verb that selects only a Theme that is mapped noncanonically as the grammatical subject. This revision process may have slowed processing, resulting in longer RTs for unaccusative verbs, and differentially recruited the IFG. This interpretation for the activation is consistent with recent proposals by Bornkessel-Schlesewsky, Grewe, and Schlesewsky (2012) and Bornkessel-Schlesewsky and Schlesewsky (2013), which subsumed argument linearization under a more general function of cognitive control, as canonical argument orders need to be suppressed to give rise to noncanonical ones. The authors further proposed that the more local the relevant considerations for exerting control, the more posterior will be the predicted activations within the IFG. Since in the present study, the considerations determining argument order are purely local (namely, they arise at the word level, with no reference to syntactic structure, referential properties of the arguments, pragmatic context, etc.), our findings of a posterior IFG and adjacent activation fit well with this model. In the same vein, our findings are in line with Friederici (2012), who proposes that one role of the left IFG is to deliver syntactic predictions, e.g. predictions about argument structure, to the temporal cortex.

One final property of unaccusative verbs, which may be relevant in the current context, is that these verbs often denote telic events. This is also true to some extent for the nonalternating unaccusatives in our sample, in particular when contrasted with the unergative verbs (15 of the 18 nonalternating unaccusative, 14 of the transitive and 4 of the unergative verbs were telic). One might thus suggest that the IFG activation we observed is triggered by telicity, rather than unaccusativity. The only study we are aware of that directly investigated the neural correlates of telicity is Romagno, Rota, Ricciardi, and Pietrini (2012). Contrasting the processing of telic and atelic verbs, the authors found that telic verbs (including both unergatives and unaccusatives) elicited left hemisphere posterior MTG activation. It therefore does not seem to be the case that telicity induces IFG activation, and this suggests that our current findings are not due to this semantic characteristic.

The current results suggest a subtle refinement of Thompson and Meltzer-Asscher's (2014) model of argument structure processing with regard to the role of the left IFG. Our model emphasizes its role in processing complex sentences, particularly sentences with syntactic movement and/or non-canonical argu-

[2] The verbs in the experiment appeared with the infinitive marker *to*, which may have triggered a movement operation, as exemplified in (i). According to standard assumptions in the transformationalist literature (e.g. Chomsky, 1995), 'to' occupies a T(ense) head, selecting the VP as a complement. The functional head T carries a feature which implements the requirement that every clause has a subject, by triggering movement into its specifier. Verbs in the other conditions were likewise presented with 'to', which presumably also triggered movement of a null element into the specifier of T. However, in these cases the null element moved from the specifier of V, rather than from its complement position. Movement from specifier of V to specifier of T takes place in every simple active sentence, and is not associated with increased processing costs on a par with movement from e.g. complement position

(i)



ment mapping. As explained above, the left IFG activation found in the present study likely reflects the cost of processing verbs with noncanonical argument-structure representations, rather than syntactic structure-building at the sentence level. Thus, we propose that the model be elaborated, such that, as suggested by Friederici (2012), the posterior IFG also contributes to controlled processing of argument structure information at the lexical level.

5. Conclusion

In this study, we investigated the neural underpinnings of argument structure processing, using a lexical decision task with verbs and pseudoverbs. We found that different dimensions of argument structure complexity have different cortical instantiations. Specifically, complexity in terms of number of thematic roles elicited left posterior perisylvian activations, and the left inferior frontal gyrus was implicated in the processing of unaccusativity. These findings suggest that argument structure information is lexically associated with verbs, and processed even outside of sentence contexts. The cortical network employed for this encompasses posterior perisylvian regions, in which activation increases with the density of lexical representations, and posterior IFG, which plays a role in resolving the conflict between the predicted, default argument structure and the noncanonicity entailed by unaccusatives.

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Appendix A

Verb	Imageability	% Intransitive use (COCA)	Verb	Imageability	% Intransitive use (COCA)
Nonalternating unaccusatives			Transitives		
appear	3.65	100%	accept	3.1	1%
arrive	4.15	100%	adopt	2.9	9%
come	4	99%	betray	2.55	1%
die	5.15	99%	build	5.55	7%
disappear	4.8	99%	collect	4.35	7%
emerge	3.25	100%	cut	6.35	5%
erupt	5.6	98%	delete	4.75	3%
evolve	3.05	92%	destroy	5.25	4%
expire	2.9	99%	erase	5.5	2%
fall	6.35	100%	Fix	4.25	2%
hover	4.65	96%	hire	3.3	3%
implode	3.8	91%	wipe	6.4	10%
bloom	5.6	100%	kill	5.9	12%
prevail	2.6	100%	mark	5.1	0%
revolve	3.7	100%	polish	5.4	5%
rise	4.9	100%	repair	4.25	3%
surge	2.6	100%	murder	5.55	7%
vanish	4.3	100%	wear	5.35	1%
Alternating unaccusatives			Unergatives		
shatter	5.9	52%	blink	6.35	92%
drop	6.05	46%	crawl	6.65	99%
roll	5.9	23%	prosper	2.7	96%
bend	6.15	33%	kneel	6.4	100%
melt	5.6	52%	relax	5.25	91%
shrink	4.95	57%	nod	6.8	95%
crack	5.15	50%	perspire	5.8	99%
bounce	6.1	89%	salivate	5.55	100%
expand	4.85	28%	rest	5.1	90%
break	5.35	26%	sneeze	6.8	97%
dissolve	4.7	42%	snore	5.95	100%
explode	6.2	11%	stand	6.3	97%
open	6.05	20%	travel	6	95%
shut	5.95	21%	wait	4.55	99%
spill	6.25	72%	weep	6.3	97%
move	5.3	66%	wink	6.7	100%
spin	6.3	50%	work	5	100%
grow	5.55	83%	yell	6.35	94%

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