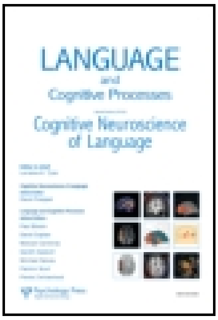

Language and Cognitive Processes
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/plcp20

The neural substrates of complex argument structure representations: Processing "alternating transitivity" verbs

Aya Meltzer-Asscher [a], Julia Schuchard [a], Dirk-Bart den Ouden [a b] & Cynthia K. Thompson [a c d]

[a] Department of Communication Sciences and Disorders, Aphasia and Neurolinguistics Research Laboratory, Northwestern University, Evanston, IL, USA

[b] Department of Communication Sciences and Disorders, University of South Carolina, Columbia, SC, USA

[c] Department of Neurology, Northwestern University, Chicago, IL, USA

[d] Cognitive Neurology and Alzheimer's Disease Center, Northwestern University, Chicago, IL, USA

Version of record first published: 06 Aug 2012

To cite this article: Aya Meltzer-Asscher, Julia Schuchard, Dirk-Bart den Ouden & Cynthia K. Thompson (2012): The neural substrates of complex argument structure representations: Processing "alternating transitivity" verbs, Language and Cognitive Processes, DOI:10.1080/01690965.2012.672754

To link to this article: http://dx.doi.org/10.1080/01690965.2012.672754

iFirst

LANGUAGE AND COGNITIVE PROCESSES, 2012, iFirst, 1–15

Psychology Press
Taylor & Francis Group

The neural substrates of complex argument structure representations: Processing "alternating transitivity" verbs

Aya Meltzer-Asscher[1], Julia Schuchard[1], Dirk-Bart den Ouden[1,2], and Cynthia K. Thompson[1,3,4]

[1]Department of Communication Sciences and Disorders, Aphasia and Neurolinguistics Research Laboratory, Northwestern University, Evanston, IL, USA
[2]Department of Communication Sciences and Disorders, University of South Carolina, Columbia, SC, USA
[3]Department of Neurology, Northwestern University, Chicago, IL, USA
[4]Cognitive Neurology and Alzheimer's Disease Center, Northwestern University, Chicago, IL, USA

This study examines the neural correlates of processing verbal entries with multiple argument structures using functional magnetic resonance imaging (fMRI). We compared brain activation in response to "alternating transitivity" verbs, corresponding to two different verbal alternates—one transitive and one intransitive—and simple verbs, with only one, intransitive, thematic grid. Fourteen young healthy participants performed a lexical decision task with the two verb types. Results showed significantly greater activation in the angular and supramarginal gyri (Brodmann areas (BAs) 39 and 40) extending to the posterior superior and middle temporal gyri bilaterally, for alternating compared to simple verbs. Additional activation was detected in bilateral middle and superior frontal gyri (BAs 8 and 9). The opposite contrast, simple compared to alternating verbs, showed no significant differential activation in any regions of the brain. These findings are consistent with previous studies implicating a posterior network including the superior temporal, supramarginal, and angular gyri for processing verbs with multiple thematic roles, as well as with those suggesting involvement of the middle and superior frontal gyri in lexical ambiguity processing. However, because "alternating transitivity" verbs differ from simple intransitives with regard to both the number of thematic grids (two vs. one) and the number of thematic roles (two vs. one), our findings do not distinguish between activations associated with these two differences.

Keywords: fMRI; Verbs; Argument structure.

Correspondence should be addressed to Aya Meltzer-Asscher, Aphasia and Neurolinguistics Research Laboratory, Frances Searle Building, 2240 Campus Drive, Evanston, IL 60208, USA. E-mail: a-meltzer-asscher@northwestern.edu

This research was supported by NIH grant R01-DC01948-17 (C.K. Thompson). The authors wish to thank Sladjana Lukic, Alex Baria, and Eisha Wali for their assistance with stimulus preparation and data collection, Jennifer Mack, PhD, for helpful comments and suggestions, and Aneta Kielar, PhD, for assistance with data analysis.

http://www.psypress.com/lcp http://dx.doi.org/10.1080/01690965.2012.672754

A central part of knowing a language is knowing the argument structure of its predicates. The argument structure of a verb forms the interface between the conceptual/semantic properties of the event denoted by the verb (e.g. how many participants the event includes) and its syntactic properties (e.g. how many noun phrases accompany the verb in a sentence). Accordingly, verbs differ with regard to the number of arguments they select, their type, and the way they are mapped onto syntactic positions. Some verbs have extremely simple argument structures, whereas others have more complex ones.

Argument structure complexity can be instantiated in different ways. One of these is the number of thematic (θ) roles a verb has, that is, verbs with fewer thematic roles (e.g. "sneeze", an intransitive verb requiring only an agent) (1) are less complex than verbs with a greater number of thematic roles (e.g. "fix", a transitive verb requiring an agent and a theme) (2):

(1) a. John sneezed.
b. SNEEZE: θ_{AGENT}
(2) a. John fixed the car.
b. FIX: θ_{AGENT} θ_{THEME}

Another criterion for complexity is the number of different syntactic realisation options of the thematic roles encoded within the verb's representation. For example, the verb "rely" has only one syntactic realisation option—it must take a PP complement (3). In contrast, "believe" can appear with three different types of complements—an NP, a PP, or a clause (4):

(3) a. John relied on Mary.
b. *John relied Mary.
c. *John relied that Mary liked him.
(4) a. John believed Mary.
b. John believed in Mary.
c. John believed that Mary liked him.

The representations in (1b) and (2b) above assume that thematic role information is listed as part of the verbal entry in the mental lexicon. This is the traditional view of the lexicon-syntax interface, to which we will refer, following Ramchand (2008), as the **lexical-thematic** approach. According to this view (Chomsky, 1981; Reinhart, 2002; among many others) the lexicon includes, for each verb, its thematic grid (or different possible thematic grids). This information is projected from the lexicon when a sentence is constructed, and the thematic information of the verb determines the number of noun phrases that appear in the sentence, for example, a transitive verb will necessitate two noun phrases.

In recent years, an opposing approach, the **generative-constructivist** approach, has emerged. Under this view, the lexicon does not include any grammatically relevant information, namely, it does not specify thematic grids. Thus, syntactic structures are not built based on the semantic/thematic information associated with verbs. Rather, syntactic building is free, restricted only by world knowledge (Borer, 2005).

In the last decades, many studies have established that argument structure complexity has neuropsychological consequences. Research across different languages, including Dutch, English, German, Italian, and Russian has shown a hierarchy of deficits in agrammatic aphasic verb production based on number of thematic roles, with 1-argument verbs presenting less difficulty than two- or three-argument verbs (Bastiaanse & Jonkers, 1998; De Bleser & Kauschke, 2003; Dragoy & Bastiaanse, 2010; Kim & Thompson, 2000, 2004; Luzzatti et al., 2002; Thompson, Lange, Schneider, & Shapiro, 1997; Thompson, Shapiro, Li, & Schendel, 1995).

Imaging studies provide further support for the mapping of argument structure complexity onto the brain. Thompson et al. (2007) and Thompson, Bonakdarpour, and Fix (2010) examined processing of one-, two-, and three-argument verbs using a lexical decision task, and found that greater complexity in terms of the number of thematic roles was associated with increased neural activation in the angular and supramarginal gyri (BAs 39 and 40) bilaterally. Similarly, Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky (2003) found activation in the left posterior superior temporal sulcus when comparing the processing of sentences with three- and two-argument verbs.[1] These posterior temporal and inferior parietal activations in response to argument structure complexity are consistent with research indicating involvement of these regions in complex semantic processing (for a review, see Binder, Desai, Graves, & Conant, 2009). Examining verb processing in sentence contexts, Shetreet, Palti, Friedmann, and Hadar (2007) also found that the medial precuneus and the anterior cingulate, not considered to be "traditional" language regions, were sensitive to the number of thematic roles a verb encodes. Finally, in a study examining naming of two-argument compared to one-argument verbs, den Ouden, Fix, Parrish, & Thompson (2009) found increased activation bilaterally in the superior parietal lobule (extending in the left hemisphere to the supramarginal gyrus) and middle temporal gyrus, as well as left hemisphere frontal regions. The authors attributed the frontal activation to the actual production process, whereas the posterior activation was considered to be associated with the processing of verbs with a greater number of thematic roles.

Complexity with respect to the number of syntactic realisation options [as exemplified in (3) and (4) above] also has been shown to have neuropsychological consequences. In a cross-modal lexical decision experiment, Shapiro, Zurif, & Grimshaw (1987) found that healthy participants display longer reaction times when processing verbs with multiple syntactic realisation options compared with simple verbs. In more recent fMRI studies with unimpaired listeners, Shetreet et al. (2007) and Shetreet, Friedmann, & Hadar (2010a) found increased neural activation in the left superior temporal gyrus, as well as in the mid-superior and inferior frontal gyri (BAs 9 and 47), in response to an increase in the number of the verb's syntactic realisation options.

The present study examines the neural representation of yet another instantiation of argument structure complexity, not explicitly targeted in previous imaging studies: the argument structure ambiguity associated with verbs with alternating transitivity. In English, a large group of lexical verb entries, labelled "alternating transitivity" verbs (Levin, 1993), correspond to two different verbal alternates: intransitive and transitive. These verbs present a basic semantic/conceptual ambiguity with regard to the type of event they denote, as they can denote both an event with one participant, and an event with two participants. Accordingly, as exemplified in (5) to (6), the same phonetic string, that is, "opened" or "rolled", can be used as an intransitive verb taking only

[1] Palti, Ben-Shachar, Hendler, & Hadar (2007) found a similar activation when contrasting the processing of verbs with that of nouns. The authors hypothesized that this activation might be due to the fact that verbs have thematic roles, whereas (concrete) nouns do not.

one NP argument (5a), (6a), or as a transitive verb, selecting for two NP arguments (5b), (6b):

(5) a. The door *opened*.
b. The teacher *opened* the door.
(6) a. The dog *rolled* (off the bed).
b. The children *rolled* the dog (off the bed).

The same alternation is found with verbs such as *close, sink, break,* and many others. In all cases, one lexical entry is associated with two different types of events and two thematic grids. That these verbs correspond to two different verbal alternates can be seen clearly in languages that have richer morphology than English. In such languages, for example, Hebrew, Polish, or Japanese, the transitive and intransitive alternates of these verbs are very often morphologically distinct (though naturally related).

The intransitive alternate of alternating transitivity verbs (5a), (6a) constitutes an unaccusative verb (Perlmutter, 1978), selecting for a single (theme) argument, which in sentences undergoes syntactic NP-movement from object to subject position (see e.g. Burzio, 1986).[2] In the generative linguistic literature, the alternation in (5) and (6) is thus referred to as the transitive–unaccusative (sometimes also the causative-inchoative) alternation.

In contrast to alternating transitivity verbs, other verbs in English do not display the alternation exemplified in (5) to (6). These verbs are exclusively intransitive (7a), rejecting a transitive use, as shown by the ungrammaticality of (7b):

(7) a. The dog barked.
b. *The vet barked the dog. (Intended meaning: The vet made the dog bark.)

According to the **lexical-thematic** approach, the difference between alternating transitivity verbs, for example, *break*, and simple intransitive verbs, for example, *bark*, is rooted in the different lexical information associated with them. While *break* is associated with two event types, or two thematic grids (transitive and intransitive), *bark* is associated with only one. Proponents of this approach can be further divided into two: (1) The transitive and intransitive alternates are related by a lexical operation reducing the transitive alternate's external thematic role to derive the unaccusative alternate (see e.g. Chierchia, 2004; Horvath & Siloni, 2011; Levin & Rappaport Hovav, 1995). Both verbal alternates are thus listed in the lexicon, with their respective thematic grids; (2) The lexicon consists solely of abstract roots, carrying some thematic information, and not of verbs. Actual verbs are built in the syntax, by merging the root with functional elements such as a verbal head, a causative head, and so on. In the case of the transitive–unaccusative alternation, the root, for example, *break*, encodes information such that it can give rise to both transitive and unaccusative verbs; the root *bark* encodes information such that it can only become an intransitive verb. This information guides the syntactic component: for the root *break*, both a transitive and an unaccusative verb can be syntactically constructed, whereas for the root *bark*, only an intransitive verb will be built (see e.g. Embick, 2004; Marantz, 1997; Ramchand, 2008).

[2] Shetreet, Friedmann, & Hadar (2010b) examined the neural correlates of processing sentences with unaccusative verbs, and found that it was associated with activation in the left inferior frontal gyrus and middle temporal gyrus. The verbs in Shetreet et al.'s study, unlike the alternating transitivity verbs discussed here, were exclusively unaccusative and not associated with two argument structures.

In contrast to the **lexical-thematic** approach, under the **generative-constructivist** view, the verbal entry is devoid of any thematic information; the difference in verbal realisation between, for example, *break* and *bark* is attributed solely to the syntactic structure in which they appear and to general interpretational principles (see e.g. Borer, 2004). According to this view, every verbal entry has the basic capacity to realise any argument structure (for further discussion of the different theoretical accounts of the alternation, see Horvath & Siloni, 2011; Schäfer, 2009).

The thematic properties of "alternating transitivity" and simple intransitive verbs can be schematised as in (8):

(8)

a. Alternating transitivity (e.g. 'break') — transitive: $\theta_1\ \theta_2$ / intransitive: θ

b. Simple intransitives (e.g. 'bark') —— intransitive: θ

As can be seen in (8), the two verb types differ on two dimensions: first, alternating transitivity verbs have two different thematic grids, whereas simple intransitive verbs have only one; second, on the transitive use of alternating transitivity verbs, they also differ from simple intransitives in the number of thematic roles they possess: two vs. one.

The present study examined the neural correlates of processing alternating transitivity and simple intransitive verbs.[3] The verbs were presented in isolation, such that the sentential context would not restrict their argument structure.[4] Based on our previous studies, investigating the effect of number of thematic roles of verbs presented in isolation in a lexical decision task (Thompson et al., 2007, 2010), we predicted differential activation in response to alternating transitivity verbs in the supramarginal or angular gyri bilaterally, due to the greater number of thematic roles they encode on their transitive reading, and their overall greater semantic/conceptual

[3] It may seem preferable to compare activations caused by alternating transitivity verbs to those caused by so-called non-alternating unaccusative verbs, for example, *appear, fall*, selecting for a theme argument. However, in addition to the fact that the latter verbs are very rare in English, several authors have argued that verbs such as *fall* in fact do have a transitive alternate, existing as a "frozen" form in the mental lexicon (see Horvath & Siloni, 2008 for theoretical arguments, and Fadlon, in press, for experimental evidence for the psychological reality of such "frozen" transitive alternates in Hebrew). If this were the case, then these verbs also would be considered alternating and the contrast between them and alternating transitivity verbs would elicit no differential activation. Another option would be to compare alternating transitivity verbs to simple transitive verbs, for example, *lock*, not displaying a transitive-intransitive alternation. As in the current design, these two verb types would differ on two dimensions: number of thematic grids (two for alternating verbs, one for transitive verbs), and, under the intransitive use of alternating transitivity verbs, also number of thematic roles (one vs. two).

[4] Although, as noted by an *LCP* reviewer, there is evidence to suggest that all argument structure options are activated with the verb, even when it appears in a sentence, where naturally only one option is realised. Such evidence was presented with regard to verbs with multiple syntactic realisation options in Shapiro et al. (1987) and Shetreet et al. (2007, 2010a). In a study investigating the processing of sentences with alternating transitivity verbs, Friedmann, Taranto, Shapiro, & Swinney (2008) attribute the inconsistent priming at the trace position to the activation of the transitive, in addition to the unaccusative, alternate of the verb.

complexity, reflected also in the fact that they have two thematic grids. The existence of multiple thematic grids can also be viewed as a type of lexical ambiguity. As such, we predicted that alternating transitivity verbs would also elicit activation in mid-superior frontal brain regions, associated in previous studies with the processing of words with multiple meanings (Chan et al., 2004; Mason & Just, 2007).

Along with the previous results mentioned above, such a result would reinforce lexical-thematic approaches to argument structure, since only under this view thematic information is listed in the lexicon and can differentiate verbs appearing in isolation. In contrast, a generative-constructivist account, stating that verbs do not carry any thematic information outside of a syntactic context, predicts no differential activation in response to alternating transitivity as opposed to simple intransitive verbs presented in isolation, since the lexical representation of the two verb types does not differ.[5]

METHOD

Participants

Participants included 14 young healthy volunteers (11 women), with ages ranging from 19 to 29 years ($M = 23$). All were right-handed, monolingual English speakers. None had a history of neurological or psychological disease or speech, language, or learning problems. Participants signed written informed consent approved by the Institutional Review Board at Northwestern University.

Stimuli

Stimuli consisted of 96 pseudowords and 42 verbs, including 20 ''alternating transitivity'' verbs and 22 simple intransitive verbs. Verbs were classified as members of these groups based on Levin and Rappaport Hovav's (1995) identification of verb classes and their members. Specifically, the alternating verbs all belonged either to the class of nonagentive verbs of manner of motion, or to the class of externally caused verbs of change of state. Verb in both of these classes exhibit a transitive–intransitive alternation, and are shown by Levin and Rappaport Hovav (1995) to exhibit unaccusative properties on their intransitive use. Stimuli were presented visually in capital letter strings. All verbs were presented in the infinitive form, as in *break* and *sing*. The two verb classes were matched for number of syllables, t (40) = 0.15, $p = .88$, and for frequency of occurrence according to the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993) (M log alternating transitivity verb frequency = 1.46; M log simple verb frequency = 1.23, t (40) = 1.47, $p = .15$). Since verb–noun ambiguity is very widespread in English, many of the verbs in both groups (15 of the 20 alternating verbs and 16 of the 22 simple verbs) had an additional, nominal reading. However, the relative frequency of this reading compared to the verb frequency of the word was generally small, and did not differ between the two verb groups, such that the degree of lexical-class ambiguity was similar in the two verb classes (M nominal frequency/verbal frequency for alternating verbs = 0.32, M nominal frequency/verbal frequency for simple verbs = 0.19, t (40) = 1.33, $p = .19$) (see Appendix 1 for the list of verbs used in the experiment).

[5] The generative-constructivist approach, for that matter, would not predict differential brain activations in response to any argument structure contrast (e.g. simple transitive vs. simple intransitive verbs) when verbs are presented in isolation, since lexical representations of verbs do not contain any thematic information.

Procedures

An event-related design was used in which words and pseudowords were visually displayed for 1,000 ms, followed by a jittered interstimulus fixation cross lasting between 1,900 and 8,700 ms. The trial order and timing of the interstimulus intervals were calculated and optimised using the OPTSEQ program (http://surfer.nmr.mgh.harvard.edu/optseq). The experiment was comprised of two runs, each including the 42 verbs along with 48 pseudowords, in different orders. Participants were instructed to respond to the letter strings by pressing a button with their left hand when seeing a pseudoword.

Data acquisition

Scanning was carried out on a Siemens Verio 3T scanner. A T1-weighted anatomical scan was made at the start of each protocol. During the experimental runs, functional volumes with BOLD contrast were obtained using gradient echo-planar imaging sequences (Time to repeat (TR) = 2,000 ms; Time to echo (TE) = 30 ms; flip angle = 90°; matrix size = 64×64; voxel size = $3.44 \times 3.44 \times 3$ mm; 31 slices).

Data analysis

Data analysis was performed with SPM8 (http://www.fil.ion.ucl.ac.uk/spm). Functional scans were realigned to a mean functional volume and corrected for slice-acquisition timing. The anatomical volume was coregistered to the mean image and normalised to the Montreal Neurological Institute 152-subject template brain (ICBM, NIH P-20 project). The functional volumes were then normalised using the same transformation, resliced to a voxel size of $3 \times 3 \times 3$ mm, and spatially smoothed using an 8 mm Gaussian kernel.

In the first-level statistical analysis, a high-pass filter of 128 seconds was used to eliminate scanner drift. For each run, six movement parameters obtained during preprocessing were entered as regressors. Additionally, an index of the degree of lexical class ambiguity of each verb (operationally defined as noun frequency/verb frequency) was incorporated as a parametric modulator into the two experimental conditions, to eliminate variability within conditions arising from this dimension of the stimuli. Individual participants' contrast maps for the alternating and simple verb conditions were then entered into second-level one-sample *t*-tests. These were evaluated at a threshold of $p < .005$, uncorrected, with a minimum cluster size (k) of 25 contiguous voxels (675 mm^3).[6]

RESULTS

Five clusters of differential activation were observed for the contrast of alternating transitivity over simple verbs, with the ambiguity index covaried out. Two large clusters were observed in the left hemisphere: one in the angular and supramarginal gyri (BAs 39 and 40), extending to the posterior superior and middle temporal gyri,

[6]This threshold was reported in several papers investigating similar linguistic contrasts (e.g. Shetreet et al.'s 2010 study of unaccusative vs. unergative verbs; Chan et al.'s 2004 study of ambiguous vs. unambiguous words in Chinese; Mason & Just's 2007 study of lexical ambiguity vs. nonambiguity in sentence contexts) as well as other subtle linguistic phenomena (e.g. Altmann, Bledowski, Wibral, & Kaiser, 2007; Santi & Grodzinsky, 2007).

and the other in the middle and superior frontal gyri (BAs 8 and 9). Two similar though smaller clusters were observed in the right-hemisphere homologues of these regions. Finally, a small activation cluster was found in the anterior cingulate (see Figure 1 and Table 1). The opposite contrast, of simple over alternating verb processing, revealed no differential activation, even using the most lenient statistical threshold.

DISCUSSION

Results of the present study show differential clusters of activation in response to the contrast between alternating transitivity verbs and simple, intransitive verbs, presented in isolation. In line with lexical-thematic accounts of argument structure, these data indicate that verbs of alternating transitivity entail a more complex argument structure representation than simple intransitive verbs, thus requiring greater processing resources, which results in recruitment of greater posterior perisylvian and middle/superior frontal tissue. Let us discuss this point in more detail.

As noted in the introduction, alternating transitivity verbs and intransitive verbs differ on two dimensions. First, alternating verbs are associated with two thematic grids (transitive and intransitive), whereas intransitive verbs are associated with only one grid. Second, the grids themselves differ between the two verb types. In particular, the alternating verbs have a transitive grid as one of their options, whereas the simple

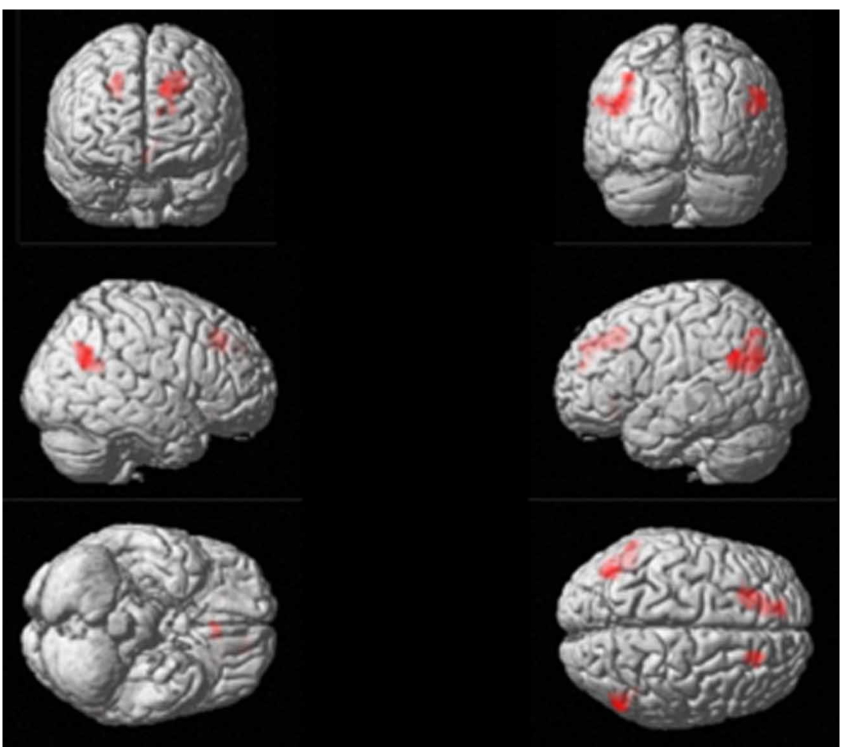

Figure 1. Differential activation for the contrast of "alternating transitivity" verbs over simple intransitive verbs ($p < .005$, uncorrected, $k \geq 25$), with relative noun frequency co-varied out. Clusters of activation are observed bilaterally in the inferior parietal lobule (BAs 39 and 40) and prefrontal cortex (BAs 8 and 9), and in the anterior cingulate.

TABLE 1
Peak Montreal Neurological Institute (MNI) coordinates, cluster sizes (*k*), maximal *t*-values, and cluster-corrected *p*-values for the clusters showing differential activation between "alternating transitivity" verbs and simple intransitive verbs ($p < .005$, uncorrected, $k \geq 25$)

		Peak coordinates					
Contrast	Region	*x*	*y*	*z*	k	t	p
Alternating > simple	LH AG, SMG, pSTG, pMTG	−39	−70	46	218	4.37	.034
	LH MFG, SFG	−12	38	34	208	4.30	.041
	anterior cingulate	−6	29	−2	32	4.42	.918
	RH AG, SMG, pSTG, pMTG	51	−61	25	109	4.32	.269
	RH MFG, SFG	−18	32	40	69	4.86	.565
Simple > alternating	None						

Notes: LH, left hemisphere; RH, right hemisphere; AG, angular gyrus; SMG, supramarginal gyrus; pMTG, posterior middle temporal gyrus; pSTG, posterior superior temporal gyrus; MFG, middle frontal gyrus; SFG, superior frontal gyrus.

verbs are invariably intransitive. Alternating transitivity verbs thus exhibit a greater number of thematic grids, as well as a greater number of thematic roles on one of these grids, than simple intransitive verbs.

Previous studies examining the effect of number of thematic roles (Ben-Shachar et al., 2003; den Ouden et al., 2009; Thompson et al., 2007, 2010) found increased posterior perisylvian activation associated with an increase in the number of thematic roles. Notably, Thompson et al. (2007, 2010), who used the same lexical decision task as the one used here, with one-, two-, and three-argument verbs, found an effect of number of thematic roles only in bilateral posterior perisylvian regions, with activation peaks very close to the posterior peaks found in the current experiment. It is thus reasonable to suggest that the posterior activations identified in the present study reflect, at least in part, the fact that alternating verbs have a transitive thematic grid (as one of their thematic options), whereas simple verbs are intransitive. These results thus reinforce the role of the angular and supramarginal gyri in both hemispheres in processing verbs with multiple thematic roles. More generally, they are in line with the many findings showing involvement of the inferior parietal lobule in semantic tasks, as verbs with more thematic roles denote more complex events, involving more participants. Binder et al.'s (2009) meta-analysis shows that the angular gyrus is the region most consistently implicated in semantic processing tasks. While activations due to semantic processing in this analysis were more common in the left hemisphere, there were many activation foci in the right angular gyrus, in line with the current results, showing right hemisphere posterior perisylvian recruitment associated with semantic complexity.

In addition to a greater number of thematic roles, however, alternating verbs also exhibit a greater number of thematic grids than simple intransitive verbs, as explained above. We suggest that this difference is reflected in the frontal activations we found in the middle and superior frontal gyri (BAs 8 and 9), which were associated with processing of alternating transitivity verbs. These regions were not implicated in the studies mentioned above investigating only number of thematic roles. They were, however, detected in a number of studies targeting the processing of lexical items associated with several interpretation options. Chan et al. (2004) found differential activation in this region in the left hemisphere in response to processing Chinese words with semantic ambiguity as opposed to words without such ambiguity. Similarly, Mason and Just (2007) found bilateral mid-superior frontal cortex activation during processing of ambiguous stimuli. These regions were also implicated in Ketteler, Kastrau, Vohn, & Huber's (2008) study of lexical ambiguity processing. In addition, Shetreet et al. (2007) detected activation in left BA 9 in response to processing verbs with multiple syntactic realisation options. The current results are in line with these previous studies, as alternating transitivity verbs are likewise lexically ambiguous. Interestingly, unlike prototypical cases of polysemy, the difference between the two senses of these verbs is not captured in terms of semantic features (as in e.g. *plant* the biological entity vs. *plant* the physical location), or lexical category (as in e.g. the noun *a nurse* vs. the verb *to nurse*). Rather, it can be captured in terms of the number of participants in the event (one or two). This information is reflected in the fact that these verbs have two thematic grids. Taken together, these findings suggest that mid-superior frontal regions are involved in the processing of lexical ambiguity or the consideration of multiple lexical options. This is consistent with the commonly held assumption that dorsolateral prefrontal regions in the two hemispheres play a role in general working memory and maintenance processes (see Curtis & D'Esposito, 2003; D'Esposito, 2001 for reviews).

Interestingly, in their cross-modal lexical decision experiments, Shapiro and Levine (1990) and Shapiro, Gordon, Hack, & Killackey (1993) found that Broca's aphasic individuals behaved on a par with healthy participants, displaying longer reaction times to verbs with multiple syntactic realisation options compared with simple verbs. This seems to contradict the claim made here, namely that frontal regions are involved in the processing of multiple lexical options. We note, however, that Shapiro and Levine (1990) and Shapiro et al. (1993) did not include anatomical descriptions of the lesion suffered by their aphasic participants. It is possible that the lesions involved left inferior frontal regions (as suggested by lesion analysis studies such as Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004; Kertesz, Harlock, & Coates, 1979), leaving intact the left and/or right middle superior frontal regions implicated in the processing of lexical ambiguity. Shetreet et al. (2007), who also found recruitment of left BA 9 in the processing of multiple lexical options, suggests that posterior regions may suffice in order to access lexical information (as suggested also below), accounting for the sensitivity of Broca's aphasic individuals to number of syntactic realisation options, whereas frontal regions may be crucial only for sustaining activation of multiple lexical options.

A last remark with regard to the frontal activations found in the current study is in order. Thompson-Schill, D'Esposito, Aguirre, & Farah (1997) claimed that left inferior prefrontal areas contribute to semantic search and selection. Interestingly, Chan et al. (2004) argue that their own findings are inconsistent with Thompson-Schill's hypothesis. The authors claim that although their task involved the identification of semantically ambiguous words, which hypothetically involves a high search and selection load, the activations they found were located in the left mid-superior frontal gyri, not in the left inferior frontal gyrus, as predicted by Thompson-Schill's hypothesis. However, Thompson-Schill's tasks manipulated the need to select a relevant feature of semantic knowledge from a set of competing alternatives. Our experimental task (as well as the tasks of Mason & Just, 2007, Shetreet et al., 2007, and possibly even Chan et al., 2004) entailed only activation of multiple options associated with a lexical item and not selection from among activated semantic features. Thus, the fact that neural activity was found in more superior regions is not incompatible with the claim of Thompson-Schill and colleagues.

An interesting question that cannot be answered based on our study is whether the increased number of thematic grids in the case of alternating verbs contributes also the posterior activations we found, or whether those were elicited only due to the increased number of thematic roles exhibited by alternating verbs. One possible piece of evidence to suggest that processing a greater number of thematic options involves superior temporal and inferior parietal regions comes from lesion data: several studies have shown that Wernicke's aphasic individuals do not perform normally on tasks involving verbs with multiple syntactic realisation options. For example, in Shapiro and Levine (1990) and Shapiro et al.'s (1993) cross-modal lexical decision experiments, results showed that unlike healthy controls (and Broca's aphasic individuals), participants with Wernicke's aphasia did not show on-line sensitivity to the thematic properties of the presented verbs, performing in a comparable manner on verbs that differed in complexity in terms of thematic options. Although these studies do not provide information regarding the localisation of the patients' lesions, given that Wernicke's aphasia often results from damage to posterior temporal and inferior parietal regions (e.g. Kertesz, 1977; Kertesz et al., 1979), including the angular gyrus (Dronkers et al., 2004), the insensitivity to the multiplicity of thematic options may be attributed to posterior perisylvian lesions. This would suggest that the posterior activations we found in our experiment reflect not only the processing of multiple thematic roles but also the processing of multiple thematic options. In the future, it will be interesting to compare alternating transitivity verbs to simple transitive verbs, to further test this hypothesis.

A few words are in order about the anterior cingulate activation we found. Although the detected cluster was small, this result is consistent both with Shetreet et al. (2007), who found activation in the right anterior cingulate, very close to the midline, in response to verbs with greater as opposed to smaller number of thematic roles, and with Chan et al. (2004), where this region was implicated in the processing of ambiguous stimuli. Taken together, these results suggest that although the anterior cingulate is not considered a "classic" language area, it might play a role in the processing of complex argument structures.

Finally, the findings from the present study are of interest with regard to linguistic theory. As mentioned in the introduction, there is an ongoing debate in linguistic literature about the nature of the lexicon-syntax interface. Lexical-thematic approaches hold that thematic information is present in the lexicon, whereas generative-constructivist approaches claim that verbal entries do not carry any grammatically relevant information, including argument structure specification. In our experiment, we found differential activation associated with alternating transitivity verbs and simple intransitives when these appeared in isolation. This is in line with the first approach, as it entails a lexical difference between the two verb types, which can only be attributed to argument structure. As explained in the introduction, a further split exists within the lexical-thematic view, with regard to alternating transitivity. According to one approach, both the transitive and the intransitive alternates are listed in the lexicon; the second approach argues that only a verbal root is listed, carrying the information that it can give rise to two syntactically composed verbs: a transitive and an intransitive. At present, the results of the current experiment cannot shed light on this debate. Both lexical-thematic views hold that alternating transitivity verbs exhibit an inherent ambiguity, whether reflected in the actual listing of two verbal alternates or in the information that the root can give rise to two verbal structures, and this ambiguity arguably elicited the frontal activation we found. The posterior activation too can be explained by both views. On the first account, upon encountering an alternating verb, for example, *break*, the speaker accesses its lexical entry, which includes two verbal alternates, one of them with a transitive thematic grid. This complex lexical-semantic representation elicits posterior perisylvian activation. According to the second view, a speaker encountering the root *break* will engage in building two syntactic structures, one for the intransitive verb *break* and another for the transitive one. It has been suggested by various authors (Constable et al., 2004; Cooke et al., 2002; Hasson, Nusbaum, & Small, 2006; Schlesewsky & Bornkessel, 2004) that superior temporal/inferior parietal regions are involved in syntactic processing. Thus, the posterior activations found in the current study can be attributed to syntactic structure building.

While the results can be accounted for by both lexical-thematic approaches, it is clear that they undermine a strict constructionist account, which assumes that no argument structure information whatsoever is listed in the lexicon. If that were the case, than it would be unclear why the contrast between processing the two verbal entry types should invoke any differential activation, since both verb types have similar lexical representations and are complex to the same degree.

CONCLUSION

Alternating transitivity verbs in English present an interesting case of complex argument structure representation, in which the same verb can be used either transitively or intransitively. Contrasting such verbs with simple intransitive verbs, we found activation elicited by the alternating verbs in posterior perisylvian and mid-superior frontal regions bilaterally. Although the study cannot distinguish between activations associated with increased number of thematic grids and those associated with increased number of thematic roles, our findings are consistent with previous studies indicating that processing verbs with a greater number of thematic roles involves the angular and supramarginal gyri bilaterally. The frontal activation found in our study is conceivably associated with the processing of multiple lexical options, consistent with previous results implicating this region in ambiguity processing. Finally, the differential activation found for alternating transitivity versus simple verbs strongly suggests that some thematic information is included in the lexical representation of verbs.

Manuscript received 1 April 2011
Revised manuscript received 22 February 2012
First published online 3 August 2012

REFERENCES

Altmann, C. F., Bledowski, C., Wibral, M., & Kaiser, J. (2007). Processing of location and pattern changes of natural sounds in the human auditory cortex. *Neuroimage*, *35*, 1192–1200.

Baayen, R. H., Piepenbrock, R., & van Rijn, H. (1993). *The CELEX lexical database* (Release 1) [CD-ROM]. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania.

Bastiaanse, R., & Jonkers, R. (1998). Verb retrieval in action naming and spontaneous speech in agrammatic and anomic aphasia. *Aphasiology*, *12*, 951–969.

Ben-Shachar, M., Hendler, T., Kahn, I., Ben-Bashat, D., & Grodzinsky, Y. (2003). The neural reality of syntactic transformations. *Psychological Science*, *14*, 433–440.

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, *19*, 2767–2796.

Borer, H. (2004). The grammar machine. In A. Artemis, E. Anagnostopoulou, & M. Everaert (Eds.), *The unaccusativity puzzle: Explorations of the syntax-lexicon interface* (pp. 288–331). Oxford: Oxford University Press.

Borer, H. (2005). *The normal course of events: Structuring sense Volume II*. Oxford: Oxford University Press.

Burzio, L. (1986). *Italian syntax*. Dordrecht: Reidel.

Chan, A. H. D., Liu, H., Yip, V., Fox, P. T., Gao, J., & Tan, L. H. (2004). Neural systems for word meaning modulated by semantic ambiguity. *Neuroimage*, *22*, 1128–1133.

Chierchia, G. (2004). A semantics for unaccusatives and its syntactic consequences. In A. Alexiadou, E. Anagnostopoulou, & M. Everaert (Eds.), *The unaccusativity puzzle: Studies on the syntax-lexicon interface* (pp. 60–84). Oxford: Oxford University Press.

Chomsky, N. (1981). *Lectures on government and binding*. Hague: Mouton de Gruyter.

Constable, R. T., Pugh, K. R., Berroya, E., Mencl, W. E., Westerveld, M., Ni, W., et al. (2004). Sentence complexity and input modality effects in sentence comprehension: An fMRI study. *Neuroimage*, *22*, 11–21.

Cooke, A., Zurif, E. B., DeVita, C., Alsop, D., Koenig, P., Detre, J., et al. (2002). Neural basis for sentence comprehension: Grammatical and short-term memory components. *Human Brain Mapping*, *15*, 80–94.

Curtis, C. E., & D'Esposito, M. (2003). Persistent activity in the prefrontal cortex during working memory. *Trends in Cognitive Sciences*, *7*, 415–423.

De Bleser, R., & Kauschke, C. (2003). Acquisition and loss of nouns and verbs: Parallel or divergent patterns? *Journal of Neurolinguistics*, *16*, 213–229.

Den Ouden, D., Fix, S., Parrish, T., & Thompson, C. (2009). Argument structure effects in action verb naming in static and dynamic conditions. *Journal of Neurolinguistics*, *22*, 196–215.

D'Esposito, M. (2001). Functional neuroimaging of working memory. In R. Cabeza & A. Kingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 293–328). Cambridge, MA: MIT Press.

Dragoy, O., & Bastiaanse, R. (2010). Verb production and word order in Russian agrammatic speakers. *Aphasiology*, *24*, 28–55.

Dronkers, N. F., Wilkins, D. P., Van Valin, R. D., Jr., Redfern, B. B., & Jaeger, J. J. (2004). Lesion analysis of the brain areas involved in language comprehension. *Cognition*, *92*, 145–177.

Embick, D. (2004). Unaccusative syntax and verbal alternations. In A. Artemis, E. Anagnostopoulou, & M. Everaert (Eds.), *The unaccusativity puzzle: Explorations of the syntax-lexicon interface* (pp. 137–158). Oxford: Oxford University Press.

Fadlon, J. (2012). The hidden existence of derivational gaps: A psycholinguistic study. In M. Everaert, M. Marelj & T. Siloni (Eds.), *The Theta System: Argument structure at the interface*. Oxford: Oxford University Press.

Friedmann, N., Taranto, G., Shapiro, L. P., & Swinney, D. (2008). The leaf fell (the leaf): The online processing of unaccusatives. *Linguistic Inquiry*, *39*, 355–377.

Hasson, U., Nusbaum, H. C., & Small, S. L. (2006). Repetition suppression for spoken sentences and the effect of task demands. *Journal of Cognitive Neuroscience*, *18*, 2013–2029.

Horvath, J., & Siloni, T. (2008). Adjectival passives: Active lexicon. In S. Armon-Lotem, G. Danon, & S. Rothstein (Eds.), *Current issues in generative Hebrew linguistics* (pp. 105–134). Amsterdam: John Benjamins.

Horvath, J., & Siloni, T. (2011). Causatives across components. *Natural Language and Linguistic Theory*, *29*, 657–704.

Kertesz, A. (1977). Isotope localization of infarcts in aphasia. *Archives of Neurology*, *34*, 590–601.

Kertesz, A., Harlock, W., & Coates, R. (1979). Computer tomographic localization, lesion size, and prognosis in aphasia and nonverbal impairment. *Brain and Language*, *8*, 34–50.

Ketteler, D., Kastrau, F., Vohn, R., & Huber, W. (2008). The subcortical role of language processing. High level linguistic features such as ambiguity-resolution and the human brain: An fMRI study. *Neuroimage*, *39*, 2002–2009.

Kim, M., & Thompson, C. K. (2000). Patterns of comprehension and production of nouns and verbs in agrammatism: Implications for lexical organization. *Brain and Language*, *74*, 1–25.

Kim, M., & Thompson, C. K. (2004). Verb deficits in Alzheimer's disease and agrammatism: Implications for lexical organization. *Brain and Language*, *88*, 1–20.

Levin, B. (1993). *English verb classes and alternations: A preliminary investigation*. Chicago, IL: University of Chicago Press.

Levin, B., & Rappaport Hovav, M. (1995). *Unaccusativity: At the syntax-lexical semantics interface*. Cambridge, MA: MIT Press.

Luzzatti, C., Raggi, R., Zonca, G., Pistarini, C., Contardi, A., & Pinna, G. D. (2002). Verb-noun double dissociation in aphasic lexical impairments: The role of word frequency and imageability. *Brain and Language*, *81*, 432–444.

Marantz, A. (1997). No escape from syntax: Don't try morphological analysis in the privacy or your own lexicon. *University of Pennsylvania Working Papers in Linguistics*, *4*, 201–225.

Mason, R., & Just, M. (2007). Lexical ambiguity in sentence comprehension. *Brain Research*, *1146*, 115–127.

Palti, D., Ben-Shachar, M., Hendler, T., & Hadar, U. (2007). Neural correlates of semantic and morphological processing of Hebrew nouns and verbs. *Human Brain Mapping*, *28*, 303–314.

Perlmutter, D. M. (1978). Impersonal passives and the unaccusative hypothesis. *Proceedings of the Annual Meeting of the Berkeley Linguistic Society*, *4*, 159–189.

Ramchand, G. (2008). *Verb meaning and the lexicon: A first-phase syntax*. Cambridge: Cambridge University Press.

Reinhart, T. (2002). The Theta System: An overview. *Theoretical Linguistics*, *28*, 229–290.

Santi, A., & Grodzinsky, Y. (2007). Working memory and syntax interact in Broca's area. *Neuroimage*, *37*, 8–17.

Schäfer, F. (2009). The causative alternation. *Language and Linguistics Compass*, *3*, 641–681.

Schlesewsky, M., & Bornkessel, I. (2004). On incremental interpretation: Degrees of meaning accessed during sentence comprehension. *Lingua*, *114*, 1213–1234.

Shapiro, L., Gordon, B., Hack, N., & Killackey, J. (1993). Verb argument processing in complex sentences in Broca and Wernicke's aphasia. *Brain and Language*, *45*, 423–447.

Shapiro, L., & Levine, B. (1990). Verb processing during sentence comprehension in aphasia. *Brain and Language*, *38*, 21–47.

Shapiro, L., Zurif, E., & Grimshaw, J. (1987). Sentence processing and the mental representation of verbs. *Cognition*, *27*, 219–246.

Shetreet, E., Friedmann, N., & Hadar, U. (2010a). The cortical representation of verbs with optional complements: The theoretical contribution of fMRI. *Human Brain Mapping*, *31*, 770–785.

Shetreet, E., Friedmann, N., & Hadar, U. (2010b). The neural correlates of linguistic distinctions: Unaccusative and unergative verbs. *Journal of Cognitive Neuroscience*, *22*, 2306–2315.

Shetreet, E., Palti, D., Friedmann, N., & Hadar, U. (2007). Cortical representation of verb processing in sentence comprehension: Number of complements, subcategorization, and thematic frames. *Cerebral Cortex*, *17*, 1958–1969.

Thompson, C. K., Bonakdarpour, B., & Fix, S. (2010). Neural mechanisms of verb argument structure processing in agrammatic aphasic and healthy age-matched listeners. *Journal of Cognitive Neuroscience*, *22*, 1993–2011.

Thompson, C. K., Bonakdarpour, B., Fix, S., Blumenfeld, H., Parrish, T., Gitelman, D., et al. (2007). Neural correlates of verb argument structure processing. *Journal of Cognitive Neuroscience*, *19*, 1753–1767.

Thompson, C. K., Lange, K., Schneider, S., & Shapiro, L. (1997). Agrammatic and non-brain-damaged subjects' verb and verb argument structure production. *Aphasiology*, *11*, 473–490.

Thompson, C. K., Shapiro, L., Li, L., & Schendel, L. (1995). Analysis of verbs and verb-argument structure: A method for quantification of aphasic language production. *Clinical Aphasiology*, *23*, 121–140.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left prefrontal cortex in retrieval of semantic knowledge: A re-evaluation. *Proceedings of the National Academy of Science*, *94*, 14792–14797.

APPENDIX 1

Verbs used in the experiment with their verb and noun frequency according to the CELEX database (baayen, piepenbrock & van rijn, 1993)

Verb	*Verb frequency*	*Noun freqency*	*Noun frequency/Verb frequency*
Alternating			
Break	4102	542	0.132
Drop	2551	586	0.230
Roll	1287	323	0.251
Bend	1179	179	0.152
Tear	1101	1093	0.993
Sink	892	261	0.293
Boil	768	172	0.224
Burst	682	230	0.337
Fade	643	0	0
Float	585	183	0.313
Melt	436	0	0
Shrink	364	5	0.0137
Crack	333	398	1.195
Crash	335	277	0.827
Bounce	289	39	0.135
Skid	59	40	0.678
Expand	832	0	0
Collapse	518	284	0.548
Dissolve	330	0	0
Implode	0	0	0
Mean (*SD*)			0.316 (0.354)
Unergatives			
Gallop	110	30	0.273
Laugh	3058	453	0.148
Cry	2158	526	0.244
Sing	1407	0	0
Weep	499	0	0
Swim	837	165	0.197
Breathe	791	0	0
Leap	549	141	0.257
Pray	505	0	0
Crawl	454	14	0.031
Blink	246	21	0.085
Sniff	229	26	0.114
Cough	223	211	0.946
Bark	186	126	0.677
Skip	168	23	0.137
Wink	142	59	0.415
Snore	69	20	0.290
Wander	661	0	0
Hobble	98	16	0.163
Scurry	87	3	0.034
Slither	96	0	0
Scuttle	67	16	0.239
Mean (*SD*)			0.193 (0.236)