Cortical Representation of Verb Processing in Sentence Comprehension: Number of Complements, Subcategorization, and Thematic Frames

The processing of various attributes of verbs is crucial for sentence comprehension. Verb attributes include the number of complements the verb selects, the number of different syntactic phrase types (subcategorization options), and the number of different thematic roles (thematic options). Two functional magnetic resonance imaging experiments investigated the cerebral location and pattern of activation of these attributes. Experiment 1 tested the effect of number of complements. Experiment 2 tested the number of options of subcategorization and of thematic frames. A group of mismatch verbs with different number of options for subcategorization and thematic frames was included to distinguish between the effects of these attributes. Fourteen Hebrew speakers performed a semantic decision task on auditorily presented sentences. Parametric analysis revealed graded activations in the left superior temporal gyrus and the left inferior frontal gyrus in correlation with the number of options. By contrast, the areas that correlated with the number of complements, the right precuneus and the right cingulate, were not conventionally linguistic. This suggests that processing the number of options is more specifically linguistic than processing the number of complements. The mismatch verbs showed a pattern of activation similar to that of the subcategorization group but unlike that of the thematic frames group. By implication, and contrary to claims by some linguists, subcategorization seems indispensable in verb processing.

Keywords: argument structure, fMRI, Hebrew, lexicon, neurolinguistics, syntax

Introduction
Verbs play a key role in sentence production and comprehension because they specify the relations among words in a sentence. It is well accepted that some crucial aspects of sentence processing are determined by the semantic and syntactic attributes of the verbs that appear in the sentence (Shapiro et al. 1987; Collina et al. 2001; van Valin 2001), but it is still undetermined which of these are available and accessed online. The current functional magnetic resonance imaging (fMRI) study explored the manner in which verb attributes affect sentence processing in auditory comprehension and the cortical locations that subserve the various attributes of verbs. We examined particular patterns of activation during the systematic variation of some crucial verb attributes. This, we hoped, could also bear upon certain linguistic controversies concerning the lexical representation of verbs. Specifically, we designed the study to contrast the relative contribution of semantic and syntactic factors to the various investigated verb attributes.

The 3 attributes at the center of our study concern the complements of the verb. The verbal complements are entities participating in the event described by the verb, beyond and in addition to the subject. Both the subject and the complements act as the verb’s arguments. For example, the verb give describes, as shown in example (1), an event with 3 entities: the giver—John, the receiver—Anna, and what was given—a present. In this sentence, there are 3 arguments: John, Anna, and a present. John is the subject, and Anna and a present are the 2 complements of the verb.

1. John gave Anna a present

Although the details of this are still debated, linguistic theory assumes that the representation of the verbal complements involves several types of information. Access to the lexical information concerning the complements of the verb was evident during the early stages of sentence processing (e.g., Holmes 1987; Shapiro et al. 1987, 1993; Tanenhaus et al. 1989; Boland et al. 1990; Boland 1993; Trueswell et al. 1993). The related information included the number of complements of the verb, the syntactic types of phrases that can serve as complements, and the thematic roles that the complements can receive.

Number of Complements
Different verbs have different number of complements, depending on the number of entities participating in the event described by the verb. For example, verbs like smile or sneeze (example 2) have no complements, only a subject. Verbs from this category are called inergatives; verbs that have one complement, like lost or ignore (example 3), are called transitives; and verbs that have 2 complements, like give or put (example 4), are called ditransitives or datives.

2. No complement: John smiled
3. One complement: John lost the keys
4. Two complements: John gave Anna a present

Number of Subcategorization Options
The syntactic types of phrases that can complement the verb are also assumed to be represented in the lexical entry (Chomsky 1965; Grimshaw 1979, 1981; Friederici 1995; Collina et al. 2001). For example, the verb lost can only be complemented with a noun phrase (NP), as illustrated in example (5) below, and the verb depend can only be complemented with a prepositional phrase (PP) (example 6). The verb discover can be complemented with either an NP or a finite clause (complementizer phrase [CP]), as shown in example (7).

5. John lost {the keys}_NP
6. Mary depends on {the spell checker}_PP

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7. a. John discovered {the story}NP
   b. John discovered {that the story is real}CP

The syntactic types of phrases that can be added to the verb are defined by its subcategorization (van Valin 2001; Carnie 2002). Subcategorization differentiates among types of verbs. Verbs differ both with respect to the type of subcategorization they select and with respect to the number of subcategorization options they allow. As mentioned in the previous examples, lost and depend have only one subcategorization option, whereas discover has 2 subcategorization options.

**Number of Thematic Options**

The third attribute that we consider in the current study is the thematic frames of a verb. This refers to the set of arguments associated with the verb in terms of their possible thematic roles. Thematic roles (also known as theta roles, or θ roles) are the roles performed by the various participants in an event. Very generally, they describe "who did what to whom" in the sentence. Note that this attribute was termed argument structure in some studies (Shapiro et al. 1987, 1989, 1993; Shapiro and Levine 1990; Rubin et al. 1996; Radford 1997; van Valin 2001). However, argument structure was also used to describe the number of complements (Haegeman 1995; Thompson et al. 1997; Collina et al. 2001; Carnie 2002) or the lexical information about the sentential environment of a verb, including syntactic and semantic information (Trueswell and Kim 1998; Friederici and Frisch 2000). Therefore, we termed this attribute "thematic frames," to emphasize its thematic nature.

Apart from the well-accepted thematic roles such as "agent" (the entity that performs the action or brings about some change), "theme" (the entity that the action is performed upon), and "goal" (the participant that is the target of the transfer or change), "give", we also consider more complex semantic types such as "proposition", which stands for sentential complements of verbs (Grimshaw 1979, 2006; Chomsky 1986; Shapiro et al. 1987, 1989; Rochette 1988; Pesetsky 1991; Carnie 2002).

Like with subcategorization, verbs differ not only by their possible thematic frames but also by the number of thematic options that they select: lost has only one thematic option, theme (example 8), whereas discover has 2 thematic options, theme or proposition (example 9) (some linguistic theories assume that both complementation options of discover take the role of a theme [Haegeman 1995], a claim that will further emphasize our results with respect to the necessity of subcategorization frames. We will examine this in the Discussion below).

8. a. \(<john>_{agent}\) lost \(<the\ keys>_{theme}\)
   b. \(<john>_{agent}\) discovered \(<the\ story>_{theme}\)

9. a. \(<john>_{agent}\) lost \(<the\ keys>_{theme}\)
   b. \(<john>_{agent}\) discovered \(<that\ the\ story\ is\ real>_{proposition}\)

To elucidate the differences between the number of complements and the number of options (of both subcategorization and thematic frames), let us try to conceptualize the linguistic difference between number of complements and number of subcategorization and thematic options. Many syntactic theories represent sentences using "syntactic trees" (or tree diagrams, e.g., van Valin 2001) that represent the syntactic hierarchy of the various components in the sentence. In the part of the tree that represents the verb phrase (VP), complements appear as branches and the number of complements is reflected in the number of branches (Fig. 1). Thus, phrases containing verbs with no complements have no branches for complements, phrases with transitive verbs have a single branch, and those with ditransitive verbs have 2 branches. As for the verb's options, each option gives rise to a different VP, so each option can be thought of as represented by a separate syntactic tree. Hence, access to verbs with 2 options requires the retrieval of 2 syntactic trees, and access to verbs with 3 options requires the retrieval of 3 syntactic trees. On the whole, the difference between the number of complements and the number of options may be represented linguistically as the difference between, respectively, the number of branches in a single tree and the number of trees.

The number of subcategorization options and the number of thematic options are the same for most verbs (as, e.g., in the case of the verb discover). Nonetheless, there are few verb categories that allow discrimination between the 2 attributes. One such verb category is a group of transitive verbs that has 2 subcategorization options but only one thematic option. For example, as illustrated in examples (10) and (11) below, the verb taste selects either an NP or a PP and both have the same thematic role, theme.

10. a. John tasted \({the\ soup}\)VP
    b. John tasted \({from\ the\ soup}\) VP
11. a. \(<john>_{agent}\) tasted \(<the\ soup>_{theme}\)
    b. \(<john>_{agent}\) tasted \(<from\ the\ soup>_{theme}\)

In the past 2 decades, claims have often been made to the effect that the lexical entries of verbs should consist only of thematic information, and not of subcategorization, and that subcategorization can be reduced to thematic roles (Stowell 1981; Pesetsky 1982, 1991; Chomsky 1986, 1995). For example, Chomsky (1995) claims that "subcategorization follows almost entirely from thematic-role specification" (p. 31, see also Pesetsky 1982). However, it seems that the linguistic jury is still out on the question of whether or not it is possible to dispense with subcategorization altogether, as Chomsky (1995) notes in the end of his discussion of this subject: "formal syntactic specifications in lexical entries have not been entirely eliminated in favor of semantic ones ... while much of c-selection (subcategorization) follows from s-selection (semantic properties), there is still a syntactic residue ... (p. 33)".

Transitive verbs that select different number of options for subcategorization and thematic frames will be used in the current study to evaluate through brain activations the relation
between subcategorization and thematic frames in verb processing. This may allow us to establish whether the number of thematic options by themselves may account for the patterns of activation during sentence comprehension or whether one also needs to consider the subcategorization requirements of verbs.

Another distinction that is investigated in the current study is between 2 types of clausal complements of verbs: finite clauses (that contain a finite inflected verb) and nonfinite clauses (that contain an infinitive verb). These clausal complements are semantically and syntactically different, and they are selected by different verbs and appear in different contexts (e.g., Pesetsky 1991). Whereas some verbs can select both to and that clauses (such as demand in example 12), other verbs can be complemented only by one of these clausal types. For example, start selects only nonfinite clauses (example 13, an asterisk represents an ungrammatical sentence), whereas deny selects only finite clauses (example 14). According to Pesetsky (1991), l-selection (lexical selection, which is different from select 2 options caused more errors in paraphrasing and anagram tasks than those with verbs that selected one option, suggesting that the number of a verb’s options affected processing load. No significant effect of response time (RT) was found in this study.

In a series of seminal studies involving online comprehension, Shapiro and his colleagues (Shapiro et al. 1987, 1989, 1991, 1993) used a cross-modal lexical decision task with different types of verbs. The time to make a lexical decision was seen as dependent upon the processing load of the verb. Therefore, differences in RT could be used to determine the amount of information that was needed to access the verb. In one experiment, Shapiro et al. (1987) compared the processing load of the number of subcategorization options with that of the number of thematic options, using RTs as the measure of processing load. They found increased RTs as a function of the number of thematic options but not of subcategorization options. Note that in order for the number of thematic options to increase the processing load, all options of a given verb must be activated at some stage of processing, regardless of the actual complement or the related context, and this has been reported by Shapiro et al. (1989, 1993). Importantly, also for the current study, Shapiro et al. (1987) tested whether the number of complements had an effect on access to the verb and found that, unlike the number of thematic options, the number of complements did not affect verb access: verbs with one complement did not differ significantly from verbs with 2 complements.

Other studies failed to find this effect. Schmauder (1991) and Schmauder et al. (1991) used fixation time in eye-tracking tasks and reaction time in interference tasks but found no clear evidence of either subcategorization or thematic frames effects. It is unclear what can be deduced from their null results, but the basic effect found by Shapiro and his colleagues has been replicated a number of times since the study of Shapiro et al. (1987). Another study that diverged from Shapiro et al. (1987) reexamined the verbs from the original study and found that, whereas the number of complements did affect processing load, the number of thematic options did not affect access to the verb (Ahrens and Swinney 1995).

Additional evidence regarding the number of thematic options came from studies with aphasic patients. Using the above lexical decision task, Shapiro and Levine (1990) compared 2 groups of patients: one with Broca’s aphasia and one with fluent aphasia (a heterogeneous group that consisted of 4 patients with Wernicke’s aphasia, 1 with conduction aphasia, and 1 with anoma) to a control group of healthy subjects. Patients with Broca’s aphasia showed response patterns similar to those of the normal controls. Both Broca’s aphasic patients and the control group showed online sensitivity to the number of thematic options. However, this type of sensitivity was not observed with the fluent aphasic patients, suggesting that posterior areas, including Wernicke’s area, participate in the processing of thematic frames. The involvement of Wernicke’s area in online processing of thematic frames was
confirmed in a subsequent study by Shapiro et al. (1993), in which the heterogeneous group of fluent aphasic patients was replaced with a group of Wernicke’s aphasic patients. The results were similar to those of the earlier study: patients with Broca’s aphasia, like normal controls, showed RTs that were sensitive to the number of thematic options of the verbs, whereas patients with Wernicke’s aphasia did not. Results in similar directions came from off-line studies with aphasic patients. Biran and Friedmann (2006) reported an individual with severe agrammatic aphasia who had intact knowledge of subcategorization and thematic frames in tests of production and grammaticality judgment and another individual who had conduction aphasia, who had aPASia, impaired access to predicate argument structure knowledge.

Neuroimaging studies have supported the involvement of Wernicke’s area (left superior temporal gyrus [left STG]) in the processing of verbal complements. These studies found an effect for the number of complements using isolated verbs (Thompson et al. 2005) or verbs in sentential context (Ben-Shachar et al. 2003). Subcategorization effects were revealed in an event-related potential (ERP) study (Rösler et al. 1993), in which negativity elicited by the subcategorization violation was observed in the left anterior field (Broca’s and frontal electrodes). A different ERP study (Rubin et al. 1996) found that the amplitude of P300 for verbs with 2 thematic options was higher than for verbs with only one thematic option. Latency of P300 and RT between the 2 conditions did not differ (unlike in Shapiro et al. 1987, 1991, 1993).

The above studies suggest that all 3 verb attributes are engaged during sentence comprehension in certain conditions. In the current study, we have used fMRI to identify the cortical involvement of each of these attributes. It is important to note that, as for the number of subcategorization and thematic options, we did not consider the specific semantic type or syntactic category of the arguments but the number of types or categories. Our key methodological assumption was that neural involvement would be specific to the investigated attribute if it reflected not only in simple contrasts between experimental conditions but also more strongly in a correlation between levels of activation and the number of complements or options. We refer to this correlation as “a graded pattern of activation.”

The graded pattern of activation could be expected in language areas that were involved in semantic and syntactic processing, as well as in areas that modulated working memory. As for thematic frames, we expected to find the graded pattern in Wernicke’s area following Shapiro et al. (1993) and perhaps in some other frontal regions that were known to be involved with semantics, such as Brodmann area (BA) 47 (Gold and Buckner 2002; McDermott et al. 2003). With respect to subcategorization, following Rösler et al. (1993), we expected the graded pattern to show in frontal areas, including Broca’s area. Considering the number of options a verb selects, processing may compute a number of potential alternatives, although only one is actually realized in the sentence. However, processing the number of complements requires all items to remain active online because the whole set of complements is realized each time the verb appears. Waters et al. (1995) found that the retention of thematic roles in memory when processing sentences with movement interfered with the performance of a secondary task, implying that the holding of thematic information loaded on to working memory. Therefore, because the number of complements determined the number of thematic roles that the verb assigned to its complements, we assumed that the number of complements would correlate with working memory load and expected the graded activation pattern to show in areas that were related to working memory.

In addition, we addressed 2 linguistic issues. The differentiation between subcategorization and thematic frames, together with the distinction between nonfinite and finite clauses, could allow us not only to locate brain regions that were involved in processing the above attributes but also, perhaps, to offer neurally based arguments that are relevant to some of the linguistic controversies concerning these attributes. The above considerations led us to design 2 experiments. The first experiment focused on the effect of the number of complements on brain activation, and the second focused on the number of subcategorization and thematic options. In both experiments, 3-point scales were used to identify brain regions that show graded activations.

### Experiment 1

The focus of this experiment was to identify brain regions that were sensitive to the number of complements. We did so by comparing verbs that took 0, 1, or 2 complements, presented in sentential context. This created a 3-point scale of the examined attribute. The number of subcategorization and thematic options was kept constant across conditions.

### Method

#### Subjects

The subjects were 12 healthy volunteers (8 females), aged 23–33 years (mean age 26.2 years). Subjects had normal hearing, no language impairment, and no psychiatric or neurological history. All subjects were native speakers of Hebrew, and Hebrew was their sole mother tongue. They were all right handed (as assessed by Edinburgh handedness inventory, Oldfield 1971). Two other subjects were excluded from the experiment: one because of an abrupt head movement and another due to lack of proper responses. Written informed consent was obtained from all subjects. The Tel Aviv Sourasky Medical Center and Tel Aviv University ethics committees approved the experimental protocol.

#### Materials and Procedure

Three psycholinguists judged Hebrew verbs for their number of complements. Verbs that were not agreed by all judges were tested in sentences with different number of complements. They were given to 17 native speakers for grammaticality judgment. If judged ungrammatical, those 17 judges were asked to offer an alternative correct sentence based on the same verb.

This procedure created a list of 28 verbs, 7 for each category. The categories (Table 1) were unergatives (verbs with no complements), obligatory transitives (verbs with one complement), and obligatory ditransitives (verbs with 2 complements). In addition, we included optional ditransitives (verbs with one obligatory complement and one optional complement, such as send). This category is not discussed in the present paper. All 28 verbs had only one option of subcategorization and thematic frames. The only attribute that differed among the verbs was that of the number of obligatory complements.

#### Table 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>Example for a sentence</th>
</tr>
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<tbody>
<tr>
<td>Unergatives</td>
<td>Dana shara [etnd] [b-a-rakvavat]</td>
</tr>
<tr>
<td>No complements</td>
<td>Dana sang [yesterday] [in the shower] [subject]</td>
</tr>
<tr>
<td>Transitives</td>
<td>Ron shovar [et ha-kos] [b-a-sartanu]</td>
</tr>
<tr>
<td>1 complement</td>
<td>Ron broke [the glass] [at the wedding] [subject]</td>
</tr>
<tr>
<td>Directives</td>
<td>Karen same [et ha-nachot] [b-a-ron]</td>
</tr>
<tr>
<td>2 complements</td>
<td>Karen put [the shirts] [at the closet] [at the closet]</td>
</tr>
</tbody>
</table>
Each verb appeared in 4 different sentences (example 17), forming a total of 112 sentences for the entire experiment. The verb was preceded by a person name (representing the subject) and followed by 2 constituents (Table 1): the sentences with the unergative verbs included 2 adjuncts or modifiers ("Adjunct" stands for any phrase that is not required by the verb, and can be attached to every verb) and the sentences with the ditransitive verbs included 2 complements after the verb.

17. a. Dan lost the keys in the office
   b. Ann lost a sock in the laundry
   c. Sean lost the way to the hotel
   d. Liz lost the recipe for the cake

Complements were either NP or PP, and their thematic role was either theme (for transitives and one of the complements of the ditransitives) or goal (for the second complement of the ditransitives). In all the sentences, the verb was inflected for third person singular and past tense. Half of the sentences of each condition were with a feminine subject (and hence with a verb inflected for the feminine) and half masculine. The verbs were controlled for frequency as determined by the Hebrew Word Frequency Database (http://word-freq.msc-c.huji.ac.il/index.html). Analysis of variance (ANOVA) detected no significant differences among the various conditions significant (F(2,20) = 1.08, P = 0.36 for the combined frequency of masculine and feminine forms) despite considerable variation (mean frequency = 27, 19, and 6.2 for unergatives, transitives, and ditransitives, respectively). The number of syllables in each sentence was controlled for length and ranged between 9 and 13 syllables (mean = 11.5; mean duration [ms] = 1797.4, 1775.5, and 1753.8 for unergatives, transitives, and ditransitives, respectively). There were no differences among the various conditions (F(2,27) = 0.49, P = 0.61).

Sentences were divided into 28 blocks, each comprising of 4 sentences with verbs of the same condition. Each condition repeated 7 times. Each verb appeared in a block only once. In each block, half of the sentences included a subject and a verb in a masculine form and half in a feminine form. The blocks and the sentences in each block were presented in a pseudorandom order (which was determined using Matlab) with no more than 2 subsequent blocks of the same condition. The presentation of each block lasted 15 s. Sentences were separated by silence periods of 1300 ms. A tone was heard at the end of each block to signal a 6 or 9 s of silence. During silence, subjects were instructed to concentrate on the noises of the magnetic resonance imaging (MRI) scanner. Stimuli were delivered to the subjects via MRI compatible headphones using Presentation software (http://www.neurobs.com).

Throughout the experiment, a semantic task was used to ensure that the subjects attended to the sentences and processed them fully. In this task, the subjects were asked to decide whether the event described in the sentence is more likely to happen at home or not. Responses were given during the intrablock silences (responses were not allowed before the end of a sentence or after the beginning of the following sentence). Subjects were requested to press a ‘yes’ or a ‘no’ button with their left hand fingers after the end of the sentence. For example, for a sentence like “Dan slept in the yellow tent,” subjects had to respond with no, whereas for a sentence like “Jane lent a towel to her flatmate,” subjects had to respond with yes. The number of no response in each block differed (ranging 1–3), but there were equal number of yes and no responses in the entire experiment. All responses and reaction times were recorded. Each subject completed 4 blocks of practice outside and inside the MRI scanner. Practice blocks included sentences that were similar to those used in the experiment but with verbs that were not included in the experiments.

Each experiment lasted 11.3 min, and the entire imaging session (including practices, anatomical, and functional scans) lasted approximately an hour and a half.

**Data Acquisition**

MRI scans were conducted in a whole-body 1.5-T, Sigma Horizon, LX, 8.25 General Electric scanner, located at the Whol Institute for Advanced Imaging in the Tel-Aviv Sourasky Medical Center. Anatomical images for each subject were acquired using a 3-dimensional spoiled gradient echo sequence with high resolution to allow volume statistical analyses in single subjects. The whole brain was covered by 70–80 slices, 2 mm thick (no gap). Functional MRI protocols included $T_2^*$-weighted images in runs of 220 volumes. We selected 27 sagittal slices (based on a midsagittal slice), 4 mm thick (no gap), covering whole of the cerebrum and most of the cerebellum. We used field of view of 24 cm and matrix size of 128 x 128, time repetition = 3000 ms, time echo = 55, and flip angle = 90°.

**Data Analysis**

Image analysis was performed using SPM2 (Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm/). Functional images from each subject were motion corrected, normalized to a standard echo planar imaging template, and spatially smoothed using a Gaussian filter (6-mm kernel).

The analysis assumed the general linear model (Friston et al. 1995) as implemented in SPM2. The blood oxygen level-dependent response was modeled with the canonical hemodynamic response function. The time series in each voxel were high-pass filtered (618 s) to remove low- frequency noise. Head motion parameters were added as regressors (Friston et al. 1995; Worsley and Friston 1995), as were the time periods allocated for responses.

A combined regressor for all conditions was used for modeling all the experimental conditions together for each subject individually (first-level analysis) in a parametric design. This allowed us to model the linear hemodynamic responses ( Büchel et al. 1998). For the combined regressor, a covariate was used to assign weights to the different conditions (1, 2, and 3 for unergatives, transitives, and obligatory ditransitives, respectively). Beta images of the combined regressors in each subject were used for a random-effect group analysis. In this second-level analysis, the parametric design was examined using Ftest with $P < 0.002$ and a minimum cluster size of 50 voxels.

In addition, a second design was defined, in which each condition was modeled separately. This allowed us to jointly contrast the conditions by using the specific beta weights of each condition. In this design, we used ANOVA with $P < 0.0005$ and a minimum cluster size of 50 voxels.

**Results**

Assessment of the parametric design in Experiment 1 did not yield graded activation in any of the canonical language areas (i.e., Broca’s area and Wernicke’s area; e.g., Bavelier et al. 1997; Karni et al. 2005). Graded activations were only found in right anterior cingulate (BA 32) and in right precuneus (BA 7), very close to the midline (Table 2 and Fig. 2). No other activations were revealed. The same clusters were identified when contrasting verbs with 2 complements and verbs with no complements.

**Reaction Time**

Reaction times were analyzed using ANOVA, and, as expected, no differences were found between the different conditions ($P > 0.19$).

**Experiment 2**

The second experiment manipulated the number of options of both subcategorization and thematic frames. Here, we compared sentences that included verbs of 1, 2, and 3 options where nonfinite clauses stood as a different semantic and syntactic category than finite clauses. We did not consider the specific semantic type or syntactic category of the arguments but only the number of subcategorization or thematic options. This created a 3-point scale for both subcategorization and thematic options. Whereas in Experiment 1, we kept the number of subcategorization and thematic options constant and manipulated the

<table>
<thead>
<tr>
<th>Region</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Cluster size</th>
<th>t-Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precentral</td>
<td>16</td>
<td>-64</td>
<td>33</td>
<td>122</td>
<td>6.29</td>
</tr>
<tr>
<td>Anterior cingulate</td>
<td>10</td>
<td>33</td>
<td>30</td>
<td>93</td>
<td>6.21</td>
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</tbody>
</table>
number of complements, in Experiment 2, we kept the number of complements constant and manipulated the number of options: the verb categories in this experiment differed by the number of subcategorization and thematic options. It is important to note here that the verbs used in this experiment selected one complement only. This allowed us to avoid some of the nonlinguistic effects that were evident in Experiment 1.

In addition, we included verbs with 2 subcategorization options but only one thematic option (we shall refer to them as 'subcat-thematic mismatch' verbs) in an attempt to differentiate between the effect of the number of subcategorization options and that of the number of thematic options. Another distinction, between nonfinite and finite clauses, was addressed. By making these distinctions, we hoped to be able to offer a neurally based clarification to the linguistic debate regarding subcategorization and thematic options.

Method

Subjects
Fourteen healthy volunteers (9 females), aged 23-33 years (mean age 26.2 years), participated in the study. Subjects had normal hearing, no language impairment, and no psychiatric or neurological history. All subjects were native speakers of Hebrew, and Hebrew was their sole mother tongue. They were all right handed (as assessed by Edinburgh handedness inventory, Oldfield 1971).

Materials and Procedure
The same team of psycholinguists as in Experiment 1 judged verbs according to their number of subcategorization options and thematic options. The procedure for nonagreed verbs was the same as in Experiment 1. Twenty-eight verbs were used, 7 in each category. There were verbs with 1 option (obligatory transitives), 2 options, and 3 options of both subcategorization and thematic frames (Table 3). A fourth category, called subcat-thematic mismatch verbs, consisted of special transitives that had 2 subcategorization options but only one thematic option.

As in Experiment 1, each verb appeared in 4 different sentences (example 17 above) and was preceded by a name, but it was always followed by a complement and an adjunct or a modifier (Table 3). Here too, the complements that appeared in the presented sentences were always either NP or PP (both bearing the theta role of theme).

Table 3
<table>
<thead>
<tr>
<th>Example sentences from each condition in Experiment 2</th>
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<tbody>
<tr>
<td>Condition</td>
</tr>
<tr>
<td>1-option verbs</td>
</tr>
<tr>
<td>2-option verbs</td>
</tr>
<tr>
<td>3-option verbs</td>
</tr>
<tr>
<td>Subcat-thematic mismatch verbs</td>
</tr>
</tbody>
</table>

In the 2-option verbs, the complement options were NP/PP theme and either CP/proposition or IP/event. In the 3-option verbs, the complement options were NP/PP theme, CP/proposition, and IP/event. No other options, such as interrogatives or exclamations (Grimshaw 1979), were possible as complements. All other parameters (inflection, length, etc.) were the same as in Experiment 1. Frequency was tested as in Experiment 1, and the 4 verb categories did not differ on frequency (F3,27 = 0.35, \( P = 0.79 \)) for the combined frequency of masculine and feminine forms) despite considerable variation (mean frequency = 10, 30, 24, and 16 for 1-, 2-, 3-option, and mismatch verbs, respectively). In addition, no differences of duration were found in the various conditions (F3,27 = 1.04, \( P = 0.37 \); mean duration = 1810.4, 1784.3, 1779, and 1867.3 for 1-, 2-, 3-option, and mismatch verbs, respectively).

The experimental design, the procedure, and the semantic task were identical to those of Experiment 1.

Data Acquisition
Parameters of data acquisition were the same as in Experiment 1.

Data Analysis
Preprocessing was the same as in Experiment 1. Similar to Experiment 1, a combined regressor was used with a covariate assigning weights to 3 of the 4 conditions (1, 2, and 3 for 1-, 2-, and 3-option verb, respectively). We will refer to this as the original parametric design. Here too, beta images were used for a random-effect group analysis and t-test, with \( P < 0.002 \) and a minimum cluster size of 50 voxels. Two more parametric analyses were used to test the differences between subcategorization and thematic options (see Results).
In addition, areas that showed graded activation in the original parametric design were defined as regions of interest (ROIs) using MarsBar (http://marsbar.sourceforge.net). The ROIs were entered to a second design in which each of the 4 conditions (1, 2, and 3 options verbs and the subcat-thematic mismatch group) was modeled separately. This allowed us to jointly contrast subcategorization with thematic frames and nonfinite clauses with finite clauses by using the specific beta weights of each condition. In this design, we used ANOVA with $P < 0.0005$ and a minimum cluster size of 50 voxels.

**Results**

The number of subcategorization and thematic options yielded significant activations in language areas, unlike the number of complements. The assessment of the parametric design in Experiment 2 revealed activations in left STG (BA 22) and in 2 clusters in left inferior frontal gyrus (left IFG): one in BA 9 and the other in BA 47 (Table 4 and Fig. 3). These areas were used as functional ROIs in some of the following analyses.

**Subcategorization Options versus Thematic Options**

We first used a separate-conditions design in which each condition was defined separately and the ROIs were defined by the parametric design. Using MarsBar, we extracted the average beta weights for each of the 3 clusters (Fig. 4), so there were $3 \times 4$ beta weights for each subject (clusters $\times$ conditions). Using $t$-tests, we compared the average weights of the mismatch verbs to both the 1-option and the 2-option groups. In all clusters, the difference between the beta weights of the subcategor-thematic mismatch verbs and the 1-option verbs was significant ($t_{13} = 1.85, P = 0.001$; $t_{13} = 9.66, P = 0.003$; $t_{13} = 2.08, P = 0.002$ in left STG, left IFG BA 9, and left IFG BA 47, respectively), whereas the difference between the beta weights of the subcategor-thematic mismatch verbs and the 2-option verbs was not ($P = 0.67$; $P = 0.1$; $P = 0.08$ in left STG, left IFG BA 9, and left IFG BA 47, respectively).

Next we performed another analysis, Analysis A, that included 2 parametric calculations in which the subct-thematic mismatch verbs replaced either the 1-option verbs (design A1) or the 2-option verbs (design A2). The weights of the replaced condition were assigned to the subcat-thematic mismatch verbs (Table 5). This was done in order to examine the similarity between the mismatch verbs (which included 2 subcategorization options but only one thematic option) and its 2 comparison groups: the 1-option verbs and the 2-option verbs. We then compared the results of the original parametric design to each of these 2 additional designs. In our reasoning, similarity of the original results to the results of design A1 would imply that it was thematic frames that played the critical role in processing, whereas similarity to the results of design A2 would imply that subcategorization played the critical role.

The results showed that the original parametric design resembled design A2: both showed graded activations in the same 3 clusters (left STG, left IFG at BA 47, and left IFG at BA 9; Table 4). By contrast, in design A1, only one cluster was identified in the left precuneus.

Finally, we approached the same issue from a slightly different angle. In this analysis, all 4 conditions were included (Analysis B in Table 5). Again we used 2 designs: in the first (design B1), we assigned the weight 1 to the subcat-thematic mismatch verbs (identical to the weight given to the 1-option verbs), whereas in the second (design B2), we assigned the weight 2 to the mismatch verbs (identical to the weight given to the 2-option verbs). Again, the results of the 2 designs were compared with the results of the original parametric design. Similarity to design B1 would imply that it was thematic frames that played the critical processing role, whereas similarity to the design B2 would imply that subcategorization played the critical role. Like with the earlier analysis (above), the results of design B1 identified only the precuneus cluster for graded activation, whereas design B2 was similar to the original parametric design in identifying graded activations in left STG, BA 47 and BA 9 (Table 4).

**Nonfinite versus Finite Clauses**

The distinction between nonfinite and finite clauses was part of the parametric design because the verbs in the 3-option category selected both finite and nonfinite clauses. The graded activations found in this design indicated that 2-option verbs (which selected either IP/event or CP/proposition) and 3-option verbs (selecting both IP/event and CP/proposition) were indeed different.

To address this question more directly, we used the separate-conditions design and the beta weights that were extracted from the ROIs of the original parametric design. Three-option verbs included both finite and nonfinite clauses, whereas 2-option verbs included only one of the clause types. The pattern of activation of the 2 types of clauses would be similar if their lexical representations were identical. However, an activation difference between them would imply that their lexical representations were distinct. Therefore, we compared the average beta weights of the 3-option verbs with those of the 2-option verbs (using $t$-tests). In BA 47, the beta weights of the 3-option verbs were significantly greater than the beta weights of the 2-option verbs ($t_{13} = 7.5$, $P = 0.038$). In the 2 remaining clusters (left STG and BA 9), the beta weights of the 2 categories did not significantly differ.

**Table 4**

Coordinates of graded activation clusters found in Experiment 2

<table>
<thead>
<tr>
<th>Region</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Cluster size</th>
<th>t-Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original parametric design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STG</td>
<td>-59</td>
<td>-52</td>
<td>12</td>
<td>52</td>
<td>4.76</td>
</tr>
<tr>
<td>IFG—BA 47</td>
<td>-36</td>
<td>19</td>
<td>-8</td>
<td>60</td>
<td>5.83</td>
</tr>
<tr>
<td>IFG—BA 9</td>
<td>-48</td>
<td>11</td>
<td>29</td>
<td>108</td>
<td>5.62</td>
</tr>
<tr>
<td>Design A1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precuneus</td>
<td>-8</td>
<td>-58</td>
<td>49</td>
<td>87</td>
<td>6.19</td>
</tr>
<tr>
<td>Design A2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STG</td>
<td>-59</td>
<td>-52</td>
<td>12</td>
<td>54</td>
<td>4.66</td>
</tr>
<tr>
<td>IFG—BA 47</td>
<td>-36</td>
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<td>-8</td>
<td>58</td>
<td>5.71</td>
</tr>
<tr>
<td>IFG—BA 9</td>
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<td>29</td>
<td>108</td>
<td>5.57</td>
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<tr>
<td>Design B1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precuneus</td>
<td>-8</td>
<td>-58</td>
<td>49</td>
<td>57</td>
<td>4.41</td>
</tr>
<tr>
<td>Design B2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STG</td>
<td>-59</td>
<td>-52</td>
<td>12</td>
<td>53</td>
<td>4.71</td>
</tr>
<tr>
<td>IFG—BA 47</td>
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<td>IFG—BA 9</td>
<td>-48</td>
<td>11</td>
<td>29</td>
<td>106</td>
<td>5.62</td>
</tr>
</tbody>
</table>

**Figure 3.** Graded activation clusters found in Experiment 2: left STG and left IFG (both BA 47 and BA 9).
The weights assigned to the different conditions in the original parametric design, analysis A and analysis B.

<table>
<thead>
<tr>
<th>Weights</th>
<th>Original parametric design</th>
<th>Analysis A</th>
<th>Analysis B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 option</td>
<td>Mismatch</td>
<td>1 option</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mismatch</td>
<td>1 option</td>
</tr>
<tr>
<td>2</td>
<td>2 options</td>
<td>2 options</td>
<td>Mismatch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 options</td>
<td>2 options</td>
</tr>
<tr>
<td>3</td>
<td>3 options</td>
<td>3 options</td>
<td>3 options</td>
</tr>
</tbody>
</table>

Reaction Times

Reaction times were analyzed using ANOVA. A Scheffe post hoc test found that the reaction times for the mismatch condition were significantly longer than the reaction times of the other conditions (P = 0.02). Note that this difference went contrary to both our expectations and the imaging results, so it could not explain the identified activations.

Discussion

The current study explored the cortical locations and the patterns of activation of three semantic-syntactic attributes of verbs that were believed to participate in online sentence processing: the number of complements, the number of subcategorization options, and the number of thematic options. The main finding was that whereas increasing the number of subcategorization and thematic options yielded graded activation in language areas, increasing the number of complements did not. Our results also bear on open questions in linguistics with respect to the representation of subcategorization and the separate representation of finite and nonfinite clause complements.

Experiment 1 investigated the activation patterns that were associated with the number of complements. We identified 2 clusters that showed graded activation according to a 3-point gradient of the tested attribute. These were located in the right precuneus and in the right anterior cingulate but not in language areas. Experiment 2 investigated the patterns of activation associated with subcategorization and thematic options. Three clusters of graded activation were identified, 1 in left STG and 2 in left IFG; in BA 47 and in BA 9. Note that, by contrast to Experiment 1, all 3 clusters were in the left hemisphere. Below, we discuss possible implications of these results and their relevance for the understanding of sentence processing.

The areas found in Experiment 1, right precuneus and right anterior cingulate, had not traditionally been considered language areas. The precuneus seemed to be involved in visual imagery (Fletcher et al. 1996), suggesting the possibility that the graded activation found in this area concerned the imagistic retention of the entities included in the sentences. The number of entities that participated in an event described by a verb was represented by the number of complements. Because most entities included in the sentences used in Experiment 1 were imageable, the number of imageable entities in these sentences correlated with the number of complements. Hence, most of the sentences that included unergative verbs consisted of only one imageable entity; most of the sentences that included transitive verbs consisted of 2 imageable entities; and so on. Thus, it may well be that, while processing these sentences, the related entities were held in imagistic form and required graded imagistic resources. This could give rise to a correlation between levels of neuronal activation and the number of complements in the right precuneus.

In addition, we expected the number of complements to load on to working memory resources due to the need to retain a greater amount of information as the number of complements increased. Indeed, activations in the anterior cingulate were observed in relation to working memory load (Awh et al. 1996; Schumacher et al. 1996; Smith et al. 1996; Braver et al. 1997). Remarkably, the part of the anterior cingulate that was activated in the present study (BA 32) was said to play a role in speech due to its connections with the auditory cortex (Paules et al. 1993). However, the absence of similar activations in frontal areas that were found to sustain working memory might restrain this argument and might indicate the involvement of other functions associated with this region, such as response monitoring (Paules et al. 1993; Carter et al. 1998; Barch et al. 2000) or, more likely, decision making (Elliott and Dolan 1998; Paulus et al. 2001, 2002). The available data could not resolve this matter.

By contrast to Experiment 1, the regions found in Experiment 2 comprised the classical language regions. Left STG forms a part of Wernicke's area and was expected to show activation when manipulating the number of a verb's options. This prediction arose directly from the study of Shapiro et al. (1993), which investigated the performance on a lexical decision task of Broca's aphasic patients, Wernicke's aphasic patients, and normal controls. Using RTs as a measure of processing load, Shapiro et al. (1993) found that normal controls and patients with Broca's aphasia were sensitive to the number of thematic options, whereas patients with Wernicke's aphasia were not. They inferred that the number of complementation options of verbs was processed in Wernicke's area.

Wernicke's area was also suggested, based on language deficits of patients with Wernicke's aphasia, to be involved in

Figure 4. Beta weights extracted from graded activation clusters in left IFG BA 9 (left) and in left STG (right).
access to the semantic properties of words (Milberg and Blumstein 1981; Blumstein et al. 1982; Mesulam 1998). Because more pieces of information needed to be handled, retrieval of verbs with greater number of options was assumed to generate a greater processing load on both word and sentence levels. This could explain the graded activation found in left STG. Additionally, Wernicke’s area had also been associated with the semantic processing of sentences (Fletcher et al. 1995; Sakai et al. 2001; Vigneau et al. 2006). Indeed, activations in this area were found while contrasting well-formed sentences with semantically ill-formed sentences (Luke et al. 2002), as well as while contrasting sentences in different languages (Schloesser et al. 1998). In a meta-analysis of similar studies, Vigneau et al. (2006) suggested that the left STG was involved with semantic integration of complex linguistic information. Semantic integration was expected to play a role in the current study because the number of options of a verb could indicate that a larger amount of semantic properties needed to be integrated in order to generate a stable sentence meaning. However, it is not self-evident that the graded activation in left STG originated in thematic options, usually considered a semantic attribute. Based on the experimental design, this activation could also arise from the number of subcategorization options. It might just be that left STG is where thematic frames and/or subcategorization are stored.

The 2 additional clusters identified in Experiment 2 are located in the left IFG, one in BA 47 and one in BA 9. Whereas BA 9 is mostly associated with working memory (Cabeza and Nyberg 2000), BA 47 has shown repeated involvement in semantic processing across a range of tasks (Polk and Prather 1989; Gold and Buckner 2002; McDermott et al. 2003; for review, see Bookheimer 2002). Both areas are believed to be involved with semantic memory (Demb et al. 1995; Gabrieli et al. 1996; Lee et al. 2002; Shivde and Thompson-Schill 2004; for review, see Bookheimer 2002).

The nature of the semantic processes subserved in these areas of the left IFG had been investigated by Thompson-Schill et al. (1997). They argued that the left IFG activity did not concern semantic retrieval per se but rather the selection of competing alternatives from semantic memory (also see Thompson-Schill et al. 1999, 2006; Fletcher and Henson 2001). Indeed, BA 9 was one of the areas within the left IFG that lighted up in a high-selection versus low-selection comparison performed by Thompson-Schill et al. (1997). By inference, regions that had a role in the selection of semantic information were likely to load according to the number of options a verb could select.

However, other studies suggested that the selection mechanism in the left IFG also applied to functions other than semantic processing (Rowe et al. 2000; Zhang et al. 2004). One such approach was suggested by Grodzinsky et al. (1993) following studies that investigated individuals with agrammatic Broca’s aphasia, who had damage in the left IFG (Swinney and Prather 1989; Grodzinsky et al. 1993). Grodzinsky et al. (ibid) claimed that the patients were impaired in the ability to jointly hold several options in order to perform a computation that would lead to the selection of one of them. They referred to this ability as a part of working memory. This implied that the left IFG, or specific areas within it, was involved in holding several activated options to allow selection.

Although Grodzinsky et al. (1993) did not discuss the exact areas within the left IFG that were involved in option selection, later studies indicated that they were similar to those activated in our study. For example, Petrides’ model of frontal function (Petrides 1995) proposed that the ventrolateral regions (which included BA 47) were responsible for selecting and deciding the relevance of information for a given task, and as mentioned before, BA 9 was identified by Thompson-Schill et al. (1997).

Interestingly, the Broca’s patients in Shapiro and Levine (1990) and Shapiro et al. (1993) showed normal sensitivity to thematic options (referred in their study as argument structure). This might be explained by splitting the processing of complement options between Broca’s and Wernicke’s areas. Access to lexical information about the number of complement options could be performed in the left STG that was spared in the Broca’s patients. The spared left STG could suffice to create RT sensitivity to the number of complementation options, even if the subsequent processes of holding the options activated and selecting among them were impaired.

In addition to identifying the cortical areas that were involved in processing the investigated verb attributes, we also considered 2 open questions in linguistics. Both concerned the distinction between opposing linguistic approaches, one regarding non-finite clauses and one regarding subcategorization. The pattern of activation revealed in Experiment 2 allowed us to present neural-based arguments appertaining to the linguistic debates.

Regarding the finite and non-finite clauses, we speculated that the lexical representation of finite clausal complements of a verb would differ from that of nonfinite clausal complements, based on their syntactic and semantic differences (Pesetsky 1991). The results of Experiment 2 supported this speculation. We compared 3-option verbs that included both clause types with 2-option verbs that included only one type, expecting that distinct lexical representations would manifest in a difference of activational patterns. Although the difference between 2- and 3-option verbs was significant only in BA 47, in all 3 regions a graded activation was revealed. These graded activations indicated that the representation of the 2 clausal complement types was different due to the inclusion of the finite–nonfinite distinction in the parametric design. Our results did not indicate whether this distinction was based on subcategorization (CP vs. IP) or on thematic frames (proposition vs. event) as the stimuli could be described as differing in both attributes.

In order to differentiate between subcategorization and thematic frames, we investigated another verb category that formed a subset of transitive verbs and subcat–thematic mismatches. These mismatch verbs selected 2 subcategorization options and 1 thematic option and showed activations similar to another group of verbs that selected 2 options of both subcategorization and thematic frames. Because similar number of subcategorization options showed similar activations, we inferred that subcategorization played a critical role in the online processing of sentences. Thus, our findings support the idea that the representation of subcategorization is separate from the representation of thematic frames (e.g., Grimshaw 1979) and that it affects online sentence processing. By inference, our results ran contrary to claims that the representation of complementation options could be reduced to the representation of thematic roles, as had been suggested by Pesetsky (1982, 1991) and Chomsky (1986, 1995).

Additional support for the role of subcategorization in processing load came from linguistic theories that allowed only a limited set of basic thematic roles (e.g., Haegeman 1995). Whereas we assumed that sentential complements carried
a thematic role of proposition or event, these theories rejected such complex semantic types, and the thematic role they assigned to the clausal complement was theme (example 21). According to such analysis, our 2-option and 3-option verbs would be viewed as having only one thematic option (example 21) but differential subcategorization options (example 22). Therefore, if one held that all 3 options carried the same thematic role, the graded activations found in Experiment 2 between the 3 types of verbs would also be ascribed to subcategorization differences.

21. a. <John> \text{agent} \text{demanded} <\text{the book}> \text{theme} \\
21. b. <John> \text{agent} \text{demanded} <\text{to read the book}> \text{theme} \\
21. c. <John> \text{agent} \text{demanded} <\text{that Anna would smile}> \text{theme} \\
22. a. John demanded [the book][PP] \\
22. b. John demanded [to read the book][PP] \\
22. c. John demanded [that Anna would smile][CP]

Note that the identification of subcategorization role in verb access does not exclude online access to information about thematic frames. The latter possibility is supported by the fact that the 3 regions identified in Experiment 2 are known to have a role in semantic processing. Indeed, as regards the IFG regions, semantic processing may be their prime connection with language processing (Fiez 1997; Poldrack et al. 1999; Burton 2001). In linguistic terms, thematic frames are related to semantics, whereas subcategorization is considered a formal syntactic attribute. Thus, it seems that our results could indicate either the additional lexical-syntactic nature of these areas or the involvement of thematic frames in the access to the verb's lexical information (Botwinik-Rotem [forthcoming] argued that the 2 options of complements that the verb \textit{taste} selects have different thematic roles. She suggests that the NP complement [example 11a] is assigned with the thematic role theme and the PP complement [example 11b] is assigned with the thematic role "subject matter." The current results may be taken as support for her view). Other findings could also bear upon the manner in which thematic frames influenced processing load (Shapiro et al. 1987, 1991, 1993; Rubin et al. 1996). Of special importance was the study by Shapiro et al. (1987), which also compared subcategorization with thematic frames and concluded that the latter was more crucially tied up with processing load. In that study, RTs for lexical decision were found to increase as a function of the number of thematic options but not as a function of subcategorization options. The discrepancy between the present findings and those of Shapiro et al. (1987) could arise in the differences between the stimulus verbs: Shapiro et al. (1987) used alternating datives and nonalternating datives.

Whereas nonalternating datives can take only NP PP complements, alternating datives can take both NP PP (gave the flowers to Mary) and NP NP complements (gave Mary the flowers). It might be that no difference was detected between these 2 types of datives not because subcategorization does not affect processing but rather because alternating and nonalternating datives actually do not differ with respect to their subcategorization. According to some theories, the 2 complementation options of the alternating datives actually form only one subcategorization option, NP PP. The NP NP option is taken to be derived from NP PP through movement (Larson 1988; Belletti and Shlonsky 1995; Ben-Shachar et al. 2004). Such an account explains why alternating and nonalternating datives did not yield any difference in RTs in Shapiro et al. (1987), as they both have only one subcategorization option.

The above considerations lead us to suggest that the processing of the number of a verb's options is essentially linguistic because it engages specifically linguistic regions. By contrast, the number of complements seems to load onto general cognitive resources and is therefore processed in networks that are not specifically linguistic. Note that our findings do not imply that information about the number of complements is not being used during sentence comprehension but only that it does not specifically load onto conventional linguistic areas and, by inference, not onto linguistic processing.

In our review of the literature, we found inconsistent accounts for the involvement of the different verb attributes in comprehension. Our results were in line with other evidence suggesting that lexical information about the verbal complements, such as subcategorization, was accessed during sentence processing (Holmes 1987; Tanenhaus et al. 1989; Boland et al. 1990; Boland 1993; Trueswell et al. 1993). In particular, our results supported the findings of Shapiro et al. (1987), as against those of Ahrens and Swinney (1995). Ben-Shachar et al. (2003) and Thompson et al. (2005) found, using fMRI, activations that corresponded to a manipulation in the number of complements. However, control for the number of subcategorization and thematic options was not reported in these studies. It could well be that the observed results in both of the above studies were mediated by the number of complementation options.

Let us now return to the syntactic tree representation of complements and options (Fig. 1). As mentioned, verbal complements are represented by branches within the VP, whereas complementation options are represented by different trees. This metaphor of branches and trees may be used to explain the results of our experiments. We found that the number of options, but not the number of complements, gives differential activations in language areas. By inference, only the number of complementation options can be regarded as a specifically linguistic property. It thus seems that when a verb is accessed, the number of branches that should be constructed within the same tree does not tax linguistic resources, whereas the number of VP trees does. We suggest that "neural linguisticity," to use a slight neologism, concerns syntactic trees rather than syntactic branches.

To conclude, this study indicates that the number of complementation options (the number of trees) that are represented in the lexical entry of the verb are accessed in the left STG, and further held for selection in the left IFG, in BA 9 and BA 47. We further suggest the neurolinguistic validity of the distinction between 2 types of clauses and support the role of subcategorization in sentence processing. Studies such as the present emphasize the importance of interfacing linguistics with neurolinguistics. These 2 disciplines should enhance and enrich each other, as well as impose constrains on one another. In this effort, neurolinguistic results can contribute to linguistic theory and linguistic theory can inform neurolinguistics, to the benefit of our understanding of both language and the brain.

Notes
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References


