The processing of different syntactic structures: fMRI investigation of the linguistic distinction between wh-movement and verb movement

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Abstract

Word order variation is a core property of sentence construction in natural languages and has been one of the most extensively studied issues in linguistics and cognitive science. In Hebrew, like in English, the basic word order is Subject–Verb–Object (SVO), but other orders, such as OSV or VSO, are also possible. According to generative syntactic theory, OSV and VSO are derived from the basic SVO order by two different types of syntactic movement: wh-movement, which moves the object to the beginning of the sentence, and verb movement, which moves the verb to a pre-subject position. Using sets of minimally-different sentences, containing the same words in different orders, we investigated the cortical activations related to the processing of these movement types. For wh-movement, we compared OSV and SVO sentences; like earlier studies of wh-movement, we found activations in the left IFG and bilateral posterior temporal regions. Activations related to verb movement were obtained through the comparison of VSO and SVO sentences, which showed activation in the left inferior occipital gyrus. Furthermore, an ROI analysis of regions that were active in the wh-movement contrast showed no difference between VSO and SVO conditions. This is the first fMRI study to compare wh-movement and verb movement, and the first to test verb movement in comprehension. The findings indicate that the different syntactic analyses assumed by linguistic theory for different word
orders are reflected in differential brain activations, lending support for the generative theory of syntactic movement and the distinction between wh-movement and verb movement.

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1. Introduction

Most English sentences have a canonical word order of Subject–Verb–Object (SVO), like in the sentence “The speaker moves the object (to the beginning of the sentence)”, where “the speaker” is the subject, “moves” is the verb and “the object” is the object. This is a simple SVO sentence constructed according to simple syntactic rules, in which the basic SVO structure is preserved. However, sentences can diverge from this order. Consider, for example, the sentence “It is the object that the speaker moved (to the beginning of the sentence)”. The meaning of this sentence is quite similar to that of the first sentence, but here the topic of the sentence is emphasized by moving the object (the phrase “the object”) to the beginning of the sentence, before the subject and the verb. The result is a syntactic structure that is complex in the sense of containing a movement. More generally, in generative grammar, such sentences are seen as derived by syntactic movement from a basic word order.

It is well accepted that sentences with non-canonical word order involve greater processing load than sentences with canonical word order. The comprehension and production of non-canonical sentences that are derived by syntactic movement are often impaired in individuals with syntactic disorders (e.g., agrammatic aphasia, Caramazza & Zurif, 1976; Grodzinsky, 1989, 1990, 2000, 2006; and developmental syntactic impairment; Friedmann & Novogrodsky, 2004, 2007, 2011; Jakubowicz, 2011; van der Lely, Jones, & Marshall, 2011; Marinis & van der Lely, 2007; Novogrodsky & Friedmann, 2006; de Villiers, de Villiers PA, & Roeper, 2011). Evidence from neuroimaging studies point in the same direction. Activations are found to increase when processing sentences with non-canonical word orders compared with canonical orders (Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Ben-Shachar, Palti, & Grodzinsky, 2004; Caplan, Alpert, & Waters, 1999; Constable et al., 2004; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Röder, Stock, Neville, Bien, & Rosler, 2002; Stromswold, Caplan, Alpert, & Rauch, 1996).

In the example above, the element that moves to the beginning of the sentence is the object of the sentence. Other constituents, such as the verb, can be moved to create other word order variations. A comparison between structures with different non-canonical word orders has not yet been conducted using neuroimaging methods. This study compares brain activations that are related to the processing of different syntactic structures that are derived by two distinct types of syntactic movement.

(1) Ha-yalda nishka et ha-doda etmol
The girl kissed ACC the-aunt yesterday

(2) Et ha-doda ha-yalda nishka etmol
ACC the-aunt the-girl kissed yesterday

(3) Etmol nishka ha-yalda et ha-doda
Yesterday kissed the-girl ACC the-aunt

According to generative syntactic theory, word order variations such as the ones exemplified in sentences (2) and (3) are derived from the canonical (base generated) order (Example 1) through a linguistic operation named syntactic movement (e.g., Chomsky, 1981, 1995; Haegeman, 1994; Fig. 1>/>). In generative theory, various types of syntactic movement are defined according to the type of element that moves and the position to which it moves. Hebrew, the language used in this study, is
relatively flexible with regard to word order, and permits orders other than the canonical Subject–Verb–Object (SVO). According to generative syntactic theory, the OSV order (in Example 2) involves the movement of the object noun phrase (NP) from its post-verbal (argument) position to the beginning of the sentence (to the Spec-CP node – the Specifier of the Complementizer Phrase), to a noncanonical preverbal position in the surface (final) structure. The movement that moves the object is called wh-movement (or A-bar movement), and it generates various structures such as wh-questions, relative clauses, and the OSV topicalization structure, demonstrated above in Example (2) and Fig. 1.

The VSO order (in Example 3) is created not by the movement of a whole phrase, but rather by the movement of a head – the verb (Lightfoot & Hornstein, 1994; Vikner, 1995. For Hebrew see Doron, 2000; Friedmann, 2013; Friedmann & Costa, 2011; Shlonsky, 1997; Shlonsky & Doron, 1992). In the type of verb movement on which the current study focuses (verb movement to the second position in the sentence), the verb moves from its original position within the verb phrase to the second position in the sentence before the subject (the C node within the CP).1 Henceforth, we use verb movement to refer to this specific type of verb movement, i.e., movement to the second position in the sentence, to the C node.2 In Hebrew, to allow this type of verb movement, a non-subject phrase needs to appear in the first position of the sentence. This is effectively what causes the verb movement to the second sentential position. In Example 3, it is the adverb “yesterday” at the beginning of the sentence that triggers a movement of the verb to the second position.

Wh-movement has been tested extensively in various sentence structures (e.g., relative clauses, wh-questions etc.), in different populations (e.g., typically developing children in the process of language acquisition, individuals with agrammatic aphasia, children with syntactic SLI, orally-trained children with hearing impairment, and healthy adults), as well as with different methods (e.g., behavioral tests, eye movement tests, cross-modal lexical priming, and neuroimaging). Verb-movement has been studied to a much lesser extent.

Individuals with agrammatic aphasia show difficulties in the comprehension and production of sentences with non-canonical orders that are derived by wh-movement. These aphasics typically understand simple active sentences, but fail to understand object relatives, object questions, and topicalization, which are non-canonical structures derived by wh-movement (Friedmann & Shapiro, 2003; Grodzinsky, 1989, 2000; Grodzinsky, Piñango, Zurif, & Drai, 1999; Schwartz, Linebarger, Saffran, & Pate, 1987; Schwartz, Saffran, & Marin, 1980; Zurif & Caramazza, 1976). Individuals with agrammatism also fail to produce sentences with relative clauses or wh-questions (Albustanji, Milman, Fox, & Bourgeois, 2010; Friedmann, 2001, 2002, 2006a,b; Friedmann, Gvion, & Novogrodsky, 2006; Fyndanis, Varlokoska, & Tsapkini, 2010; Garraffa, 2007; Ruigendijk, Kouwenberg, & Friedmann, 2004; Stadie et al., 2007).

As for the comprehension of sentences with verb movement in agrammatic aphasia, it has been initially claimed that it is not impaired (Grodzinsky, 1995, 2000), because agrammatic aphasics seemed to judge correctly the grammaticality of sentences with verb movement (Grodzinsky & Finkel, 1998;...
Linebarger, Schwartz, & Saffran, 1983; Lonzi & Luzzatti, 1993). This claim was challenged by Friedmann, Gvion, Biran, and Novogrodsky (2006), who argued that correct grammaticality judgments do not necessarily indicate unimpaired comprehension of the sentences (see Zurif & Grodzinsky, 1983; Zurif & Swinney, 1994 for discussion of grammaticality judgment and comprehension tasks). Indeed, a study that required individuals with agrammatism to interpret sentences with verb movement, rather than judge their grammaticality (and which prevented them from using a strategy according to which the first noun phrase is the agent), revealed impaired comprehension of verb movement in agrammatism (Friedmann et al., 2006). It has also been shown that individuals with agrammatism have difficulties in the production of sentences that include verb movement (Bastiaanse, Rispens, Ruigendijk, Juncos Rabadán, & Thompson, 2002; Bastiaanse & van Zonneveld, 1998; Friedmann, 1998, 2000, 2006a; Kolk & Heeschen, 1992; Zuckerman, Bastiaanse, & van Zonneveld, 2001). Thus, the comprehension and production of both wh-movement and verb movement are impaired in agrammatism, either because the processing of both movement types is impaired, or because the landing site of these movements at the top of the syntactic tree is compromised (Friedmann, 2006b; Friedmann, Gvion, & Novogrodsky, 2006; Friedmann et al., 2006).

Studies of language acquisition show that certain non-canonical structures derived by movement are acquired late (after the age of four) (Correa, 1995; De Vincenzi, Arduino, Ciccarelli, & Job, 1999; Friedmann, Belletti, & Rizzi, 2009; Friedmann & Costa, 2011; Friedmann & Novogrodsky, 2004; McKee, McDaniel, & Snedecker, 1998; de Villiers, de Villiers, & Hoban, 1994). Furthermore, children with syntactic SLI fail to establish filler-gap dependencies (Marinis & van der Lely, 2007) and have difficulties in the comprehension and production of non-canonical sentences derived by wh-movement (Friedmann & Novogrodsky, 2008, 2011; Jakubowicz, 2011; Novogrodsky & Friedmann, 2006; de Villiers et al., 2011). Developmental studies show a clear distinction between wh-movement and verb movement. A study that specifically investigated the order of the acquisition of syntactic movement (including A-movement, which is beyond the scope of the present study) showed that wh-movement is acquired before verb movement to C (Friedmann & Lavi, 2006).

Sentences with syntactic movement were also tested in healthy adults using reaction time (RT) measurements and in neuroimaging studies. Many studies examined the processing of wh-movement using a Cross-Modal Lexical Priming (CMLP) task (Hickok, Canseco-Gonzalez, Zurif, & Grimshaw, 1992; Love & Swinney, 1996; Nicol & Swinney, 1989; Swinney, Ford, Frauenfelder, & Bresnan, 1988; Swinney, Zurif, & Nicol, 1989; Zurif, Swinney, Prather, Solomon, & Bushell, 1993; Zurif, Swinney, Prather, Wingfield, & Brownell, 1995). In this paradigm, participants listen to sentences that include a moved object and are asked to perform lexical decision on visually presented probes that are positioned at critical points in the sentence. Probes related to the moved objects at the original post-verbal object position yielded shorter RTs compared with probes unrelated to the object at this position. Namely, there is priming for the object in its original position. This priming effect indicates reactivation of the meaning of the object in its original position (lending support to the theory of syntactic movement). Importantly, between the actual pre-verbal position of the object and its original position, no priming effect is found, indicating that the activation of the object has decayed and then, at the original object position, the object meaning was re-accessed. By contrast, CMLP studies of verb movement to second position (in Dutch) found a priming effect for related probes at all tested positions, including the intermediate position (de Goede, Shapiro, Wester, Swinney, & Bastiaanse, 2009). This indicates that the meaning of moved verbs remains active during the entire sentence, thus showing another difference between wh- and verb movements.

In the neuroimaging literature, syntactic structures derived by movement (typically, non-canonical orders) are found to require more cortical resources than sentences without movement. However, there is great variance with regard to the types of syntactic structures that were tested and the locations of the activated areas. Some studies have found increased activation in Broca’s area (in the left inferior frontal gyrus) when comparing sentences with and without wh-movement (e.g., Ben-Shachar et al., 2003, 2004; Santi & Grodzinsky, 2007), whereas others found activation in this area when comparing two types of constructions with wh-movement, one of which is considered more syntactically complex (e.g., center-embedded relatives vs. right-branching relatives in Caplan et al., 1999; Stromswold et al., 1996; or object relatives vs. subject relatives in Constable et al., 2004; Just et al., 1996). Additionally, some studies also found activations in Wernicke’s area and other posterior
regions (including the superior temporal gyrus, angular gyrus, and superior parietal cortex), as well as activations in its right homologue (Ben-Shachar et al., 2003, 2004; Caplan et al., 1999, 2001; Constable et al., 2004; Cooke et al., 2001; Just et al., 1996; Röder et al., 2002; Santi & Grodzinsky, 2007; Wartenburger et al., 2004. See Grodzinsky, 2006 for a summary and discussion).

Fewer neuroimaging studies tested the processing of verb movement. Den Ouden, Hoogduin, Stowe and Bastiaanse (2008) compared the production of sentences with verb movement from final to second position in Dutch to the production of sentences in the canonical SOV order. This study found increased activation in left middle and superior frontal gyrus. Thus, the pattern of cortical activation found for the production of verb movement to C seems to be different from the activations found for wh-movement comprehension, suggesting that each of the two types of syntactic movement is processed differently.

Thus, data from developmental, RT and neuroimaging studies, as well as linguistic theory, suggest that wh-movement and verb movement are processed differently. However, until now, no direct comparison between the cortical patterns of the two types of syntactic movement has been performed, and the processing of verb movement in comprehension has not been tested. These are the aims of the current fMRI study.

To examine the differences in processing wh-movement and verb movement, we constructed sets of four minimally-different sentences that included exactly the same words in different word orders. The wh-movement analysis compared sentences with wh-movement in which the object moved to the first position in the sentence (OSV), with sentences in the canonical order (SVO), which did not contain wh-movement. The verb movement analysis compared sentences in which the verb moved to the second position with sentences in the canonical order. Because in Hebrew verb movement to the second position has to follow a non-subject phrase in the beginning of the sentence, we added, in both the verb movement sentences and their control sentences, a (temporal) adverb in the first position. Thus, the verb movement comparison compared AVSO sentences with ASVO sentences. To make all four sentence conditions similar, we also added an adverb to the wh-movement sentences and their SVO controls (creating OSVA and SVOA sentences). This created minimally different sentences, which differed only with respect to the tested syntactic movement.

2. Methods

2.1. Participants

The participants in the experiment were 22 healthy volunteers (12 females) aged 22–41 (mean age: 29). They had normal hearing, no language impairment, and no psychiatric or neurological history. All participants were native speakers of Hebrew, which was their sole mother tongue. They were all right handed. Written informed consent was obtained from all participants. The Tel-Aviv Sourasky Medical Center and Tel Aviv University ethics committees approved the experimental protocol. Two additional participants were excluded from the experiment due to low rate of correct responses.

2.2. Materials and procedure

Stimuli were auditorily presented Hebrew sentences. The sentences were recorded by a native Hebrew-speaking man at 22,500 Hz sampling rate. Sentences were recorded in one session and the order of recording was randomized across conditions. Each sentence included four constituents: a Subject (S), a transitive Verb (V), an Object with a modifying adjective (O), and a temporal Adverb (A). The order of the constituents was manipulated to create four conditions (Table 1): canonical SVOA sentences, topicalized OSVA sentences, canonical ASVO sentences, and moved verb AVSO sentences. Importantly, each of these conditions included the same words in different orders. This allowed us optimal control and balance of word features such as frequency, familiarity, as well as sentence duration (mean duration (ms) = 2458.3, 2517.5, 2466.1, and 2422.5; SD = 200.4, 141.9, 222.1, and 227.6 for SVOA, OSVA, ASVO and AVSO conditions, respectively). There were no duration differences among the various conditions ($F(3,76) = 0.76, p = 0.52$). We also controlled for prosody while recording the sentences, and the conditions did not differ with respect to in peak and average pitch ($F(3,76) = 0.47, p = 0.70$ for peak, and $F(3,76) = 0.72, p = 0.54$ for average pitch).
There were 20 basic sentences, from each of which we created four sentences according to the four conditions. In total, then, there were 80 sentences for the entire experiment, 20 sentences for each condition. All versions of each sentence were presented to each of the participants in randomized order. All noun phrases in the sentences were human. The same gender was used for the subject and the object in the sentence. All the sentences were inflected for third person singular, half in the past tense and half in future tense.

The 80 sentences were divided into 20 blocks. Each block consisted of four sentences of the same structure. Each condition was repeated 5 times. Within each block, half of the sentences included masculine subject and object (and a verb inflected accordingly) and half included feminine subject and object (and a verb inflected accordingly). The blocks and the sentences in each block were presented in a pseudo-random order (determined by Matlab script), with no more than two consecutive blocks of the same condition. This script created several lists with different possible orders. We inspected the lists manually and chose four lists that were counterbalanced for the order of the presentation of the conditions (controlling for the first and last appearance of each condition). Each list was assigned to a fourth of the participants. The presentation of each block lasted 16 s. Sentences were separated by silence periods of 1450 ms. A tone was heard at the end of each block to signal 10 or 12 s of silence. During silence, participants were instructed to concentrate on the noises of the MRI scanner. Stimuli were delivered to the participants via MRI compatible headphones using Presentation software (http://nbs.neuro-bs.com).

Throughout the experiment, participants performed a semantic task to ensure that they attended to the sentences and processed them fully. In this task, the participants were requested to listen to the sentence and decide whether the event described in the sentence was positive or not. For example, for the sentence “The policeman hit the pedantic doctor yesterday”, participants had to press the “no” button; for the sentence “The grandmother will hug the excited soldier tomorrow”, participants had to press the “yes” button. There were equal numbers of predicted “yes” and “no” responses in the entire experiment, and within each block the number of predicted “no” responses ranged between 1 and 3. After the end of the sentence, participants pressed the “yes” or the “no” button with their left hand fingers (to avoid interference in frontal language areas). Responses were not allowed before the end of a sentence or after the beginning of the following sentence. All responses and reaction times were recorded.

Each subject completed short practice sessions outside and inside the MRI scanner. The four practice blocks included sentences that were similar to those of the experiment, using simple SVOA sentences that were not included in the experiment. The experiment included one run that lasted 10 min and the entire imaging session (including practices, anatomical and other functional scans) lasted approximately an hour and a half.

### 2.3. Data acquisition

MRI scans were conducted in a whole-body 3 T, General Electric scanner, located at the Whol Institute for Advanced Imaging in the Tel-Aviv Sourasky Medical Center. Anatomical images for each participant were acquired using a 3D spoiled gradient echo (SPGR) sequence with high resolution, to allow volume statistical analyses in single participants. The whole brain was covered by 144–160 slices, 1 mm thick (no gap). Functional MRI protocols included T2*-weighted images in runs of 300 volumes.

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**Table 1**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>ifiers</td>
<td>Et ha-xayelet ha-nirgeshet ha-safta texabek maxar ACC the-soldier_FEM the-excited_FEM the-grandma will-hug tomorrow</td>
</tr>
<tr>
<td>ifiers</td>
<td>Ha-safta texabek et ha-xayelet ha-nirgeshet maxar The-grandma will-hug ACC the-soldier_FEM the-excited_FEM tomorrow</td>
</tr>
<tr>
<td>ifiers</td>
<td>Maxar texabek ha-safta et ha-xayelet ha-nirgeshet</td>
</tr>
<tr>
<td>ifiers</td>
<td>Maxar ha-safta texabek et ha-xayelet ha-nirgeshet</td>
</tr>
</tbody>
</table>

*All four conditions mean “The grandma will hug the excited soldier tomorrow.”*
We selected 33 sagittal slices (based on a mid-sagittal slice), 3.5 mm thick (no gap), covering the whole of the cerebrum and most of the cerebellum. We used FOV of 20 cm and matrix size of $64 \times 64$, $TR = 2000$ ms, $TE = 30$, and flip angle $= 90$.

2.4. Data analysis

Image analysis was performed using SPM8 (Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm). Functional images from each subject were motion-corrected, normalized to the SPM EPI template, resampled with a voxel size of $3 \times 3 \times 3$ mm (Ashburner & Friston, 1999), and spatially smoothed using a Gaussian filter (8-mm kernel). Each subject’s data was analyzed using a general linear model (GLM, Friston et al., 1995). The onsets of the block for each condition were modeled with the canonical hemodynamic response function (HRF), with a duration of 16 s. Head motion parameters were added as regressors (Friston et al., 1995).

2.4.1. Whole brain analysis

For the group analysis, one-sample $t$-tests were computed using the individual contrast images. Analyses were carried out with the threshold of $p < 0.001$, cluster size of $k > 25$ voxels, and cluster-level correction of $p < 0.05$. To localize the areas of activation, and identify the related Brodmann areas (BA) we used xjView (http://www.alivelearn.net/xjview), as well as Talairach daemon software (Lancaster, Summerin, Rainey, Freitas, & Fox, 1997) (for which peak coordinates were transformed to Talairach space using mni2talsoftware, http://www.mrc-cbu.cam.ac.uk/Imaging/mnispace.html).

2.4.2. Region of interest (ROI) analysis

We performed ROI analyses for the activation clusters found in the comparison between sentences with $wh$-movement and sentences with canonical order (OSVA > SVOA). The aim of this analysis was to examine with greater sensitivity the activations related to verb movement processing within areas that were found to be involved in $wh$-movement processing. Thus, we tested data that is orthogonal to the data used to define the ROI. Average beta values of AVSO and ASVO conditions were extracted from the activation clusters using MarsBar (http://marsbar.sourceforge.net), and a simple $t$-test was performed to compare the two conditions.

To allow for a direct comparison between $wh$-movement and verb movement, we performed another ROI analysis. In this second analysis, we used coordinates from a different fMRI study that tested topicalization in Hebrew (Ben Shachar et al., 2004). We defined a 7 mm sphere around the peak coordinates of the left IFG, and left and right posterior STG, using MarsBar (http://marsbar.sourceforge.net). Average beta values for all the conditions were extracted from the activation clusters, and a repeated measures ANOVA was performed to compare the conditions.

3. Results

First, we conducted comparisons between sentences in the same minimal set. The comparison of sentences with $wh$-movement to their canonical order, control sentences (OSVA > SVOA) showed activations in classic $wh$-movement areas (Table 2, Fig. 2A): left inferior frontal gyrus (IFG; BA 44/45) and bilateral posterior temporal regions (STG/MTG, BA 22). Additional activations were found in the right IFG (BA 47), the left precentral gyrus, and the left cerebellum. No activation was found for the opposite contrast (SVOA > OSVA).

The comparison of sentences with verb movement to their canonical order controls (AVSO > ASVO) showed a single cluster of activation in the lingual gyrus/inferior occipital gyrus (IOG; BA 17; Table 2, Fig. 2B). No activation was found for the opposite contrast (ASVO > AVSO). We also compared the two canonical orders: one with the adjective in the first position and one with the adjective in the sentence-final position. No activation was found for any of these contrasts (ASVO > SVOA; SVOA > ASVO). This indicates that positioning the adverb at the beginning of the sentence does not include $wh$-movement (and is probably base-generated, namely, directly merged onto spec-CP).

Next, we performed a paired $t$-test comparison between the two main contrasts, the $wh$-movement and verb movement contrasts [OSVA > SVOA] > [AVSO > ASVO]. We found activations in the left IFG (BA...
Table 2
Coordinates (Talaraich), cluster sizes, and t values of brain regions identified in the wh-movement and verb movement analyses.

<table>
<thead>
<tr>
<th>Region</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>K (voxels)</th>
<th>p (cluster)</th>
<th>t max</th>
</tr>
</thead>
<tbody>
<tr>
<td>wh-movement compared with canonical order [OSVA &gt; SVOA]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>left IFG (BA 44/45)</td>
<td>−53</td>
<td>24</td>
<td>10</td>
<td>293</td>
<td>0.001</td>
<td>4.98</td>
</tr>
<tr>
<td>right IFG (BA 47)</td>
<td>50</td>
<td>27</td>
<td>−5</td>
<td>172</td>
<td>0.001</td>
<td>4.77</td>
</tr>
<tr>
<td>left posterior temporal (BA 22)</td>
<td>−53</td>
<td>−26</td>
<td>0</td>
<td>280</td>
<td>0.001</td>
<td>5.93</td>
</tr>
<tr>
<td>right posterior temporal (BA 22)</td>
<td>51</td>
<td>−35</td>
<td>2</td>
<td>63</td>
<td>0.002</td>
<td>4.19</td>
</tr>
<tr>
<td>left cerebellum</td>
<td>−12</td>
<td>−81</td>
<td>−26</td>
<td>131</td>
<td>0.002</td>
<td>5.00</td>
</tr>
<tr>
<td>left precentral gyrus (BA 6)</td>
<td>−48</td>
<td>−1</td>
<td>50</td>
<td>29</td>
<td>0.002</td>
<td>4.18</td>
</tr>
<tr>
<td>Verb movement compared with canonical order [AVSO &gt; ASVO]</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>left IOG/lingual gyrus (BA 17)</td>
<td>−18</td>
<td>−94</td>
<td>−7</td>
<td>29</td>
<td>0.003</td>
<td>4.37</td>
</tr>
<tr>
<td>wh-movement compared with verb movement ([OSVA &gt; SVOA] &gt; [AVSO &gt; ASVO])</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>left IFG (BA 44/45)</td>
<td>−48</td>
<td>16</td>
<td>7</td>
<td>31</td>
<td>0.01</td>
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<tr>
<td>left posterior temporal (BA 22)</td>
<td>−53</td>
<td>−31</td>
<td>0</td>
<td>110</td>
<td>0.002</td>
<td>4.67</td>
</tr>
<tr>
<td>medial superior frontal gyrus</td>
<td>6</td>
<td>48</td>
<td>34</td>
<td>278</td>
<td>0.001</td>
<td>4.59</td>
</tr>
</tbody>
</table>

Fig. 2. (A) Activations found in the comparison of sentences with wh-movement and sentences in the canonical order (OSVA > SVOA). (B) Activations found in the comparison of sentences with verb movement and sentences in the canonical order (AVSO > ASVO). (C) Activations found in the comparison of sentences with wh-movement and sentences with verb movement ([OSVA > SVOA] > [AVSO > ASVO]).
left posterior temporal regions (MTG/STG, BA 22), and in the medial superior frontal gyrus (Table 2, Fig. 2C). The same activations were identified when masking this comparison with the contrast [SVOA – ASVO]. This suggests that there is no effect for the position of the adverb within the sentence on the activations related to the AVSO order. The opposite comparison ([AVSO > ASVO] > [OSVA > SVOA]) showed no activations.

Finally we performed two ROI analyses that examined the activation related to the processing of verb movement in areas that had previously been associated with wh-movement – the left IFG and left and right posterior temporal regions. In the first ROI analysis, we examined these regions as identified in the comparison OSVA > SVOA in the current study to assess the activation of the verb movement condition (AVSO) compared with its matched canonical sentence (ASVO). In all three clusters, there was no significant difference between the two conditions (\(t(21) = 0.43, p = 0.44, t(21) = 0.32, p = 0.13, \) and \(t(21) = 1.9, p = 0.43\) for the left IFG, left posterior temporal regions, and right posterior temporal regions, respectively).

In the second ROI analysis, we defined these regions based on a previous study of topicalized OSV structure in Hebrew (Ben-Shachar et al., 2004). Using externally-defined ROIs, we were able to directly compare the critical conditions of our study: the OSVA and AVSO conditions. Repeated measures ANOVA of all our conditions was significant in the three regions (\(F(3,87) = 7.18, p < 0.001, F(3,87) = 5.45, p = 0.002, \) and \(F(3,87) = 5.52, p = 0.002\) for the left IFG, left posterior temporal regions, and right posterior temporal regions, respectively). Post-hoc Tukey HSD test further confirmed our previous findings, revealing that the wh-movement (OSVA) condition showed greater activation compared with the three conditions in all the tested regions (\(p < 0.05; \) Fig. 3). To specifically evaluate the differences between the wh-movement condition (OSVA) and the verb movement condition (AVSO), we performed a preplanned paired \(t\)-test and calculated the effect size. In the three regions, we observed significantly increased activation for the wh-movement condition, with large effect sizes: \(t(21) = 3.79, p < 0.001, d = 0.89; \) \(t(21) = 3.04, p = 0.003, d = 0.41; \) and \(t(21) = 4.15, p < 0.001, d = 0.39, \) for the left IFG, left posterior temporal regions, and right posterior temporal regions, respectively. The ROI results lends further support for the finding that verb movement is not processed in the same areas as does wh-movement.

4. Discussion

Linguistic theory suggests that different types of syntactic movement exist, yielding different types of syntactic structures. In this study, we examined the distinctive neural pattern of different syntactic structures. Generative approaches assume that Hebrew sentences with topicalization are derived by wh-movement that moves the object to the first (spec-CP) position, whereas Hebrew sentences with a verb in the second position (after an adverb in the first position) are derived by a verb movement that moves the verb to its pre-subject position (in C). We showed that the comprehension of syntactic structures derived by these different types of syntactic movement activated different brain regions. The processing of sentences derived by a wh-movement showed activations in the left IFG (BA 44/45), right...
IFG (BA 47), left and right posterior temporal regions (BA 22), the left precentral gyrus, and the cerebellum, whereas the processing of sentences with verb movement to the second sentential position showed activations in the left IOG. Thus, our results support the theoretical distinction between wh-movement and verb movement. Our results are in line with findings from language development studies (Friedmann & Lavi, 2006) and RT studies (de Goede et al., 2009), which show a clear distinction between wh-movement and verb movement.

4.1. Topicalization

Sentences derived by wh-movement, in which the object is topicalized into the first position in the sentence, compared with the same sentences without wh-movement, showed here a pattern of activation consistent with previous findings (for summary, see Grodzinsky & Friederici, 2006): activations observed in the left IFG and bilateral temporal regions. The left IFG and, specifically, Broca’s area (BA 44/45), has been consistently linked to the processing of complex syntactic structures. Individuals with agrammatic aphasia, who typically have lesions in the left IFG, show difficulties in the comprehension and production of non-canonical sentences derived by wh-movement, such as wh-questions, relative clauses, and topicalization (Friedmann, 2001, 2002; Friedmann & Shapiro, 2003; Grodzinsky, 1989, 2000, 2006; Grodzinsky et al., 1999; Grodzinsky & Santi, 2008; Hickok & Avrutin, 1996; van der Meulen, 2004; Thompson, Tait, Ballard, & Fix, 1999). Additionally, the left IFG in healthy individuals was found more active when processing syntactic structures derived by wh-movement (Ben-Shachar et al., 2003, 2004; Caplan et al., 1999; Constable et al., 2004; Just et al., 1996; Makuuchi, Grodzinsky, Amunts, Santi, & Friederici, 2013; Santi & Grodzinsky, 2007; Stromswold et al., 1996; see also Röder et al., 2002, for another type of phrase movement). Whereas many of these studies compared two structures derived by wh-movement, one of which considered more syntactically complex (e.g., object relatives vs. subject relatives), few others compared sentences with wh-movement with minimally-different sentences without movement. These studies also found increased activation in the left IFG (Ben Shachar et al., 2003, 2004).

The posterior temporal regions (i.e., Wernicke’s area and its surrounding), although traditionally linked to lexical and semantic processing (e.g., Binder, Desai, Graves, & Conant, 2009; Binder et al., 1997; Blumstein, Milberg, & Shrier, 1982; Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004; Luke, Liu, Wai, Tan, 2002; Mesulam, 1998; Milberg & Blumstein, 1981; Turken & Dronkers, 2011; Vigneau et al., 2006), consistently show increased activation in response to syntactically complex structures, including sentences derived by wh-movement (Ben-Shachar et al., 2003, 2004; Caplan et al., 1999, 2001; Constable et al., 2004; Cooke et al., 2001; Grodzinsky, 2006; Just et al., 1996; Röder et al., 2002; Wartenburger et al., 2004; also see den-Ouden et al., 2012, for a discussion in the connectivity of the two regions). Given the lexical-semantic function of this area, it is possible that the role that it plays in the comprehension of sentences derived by wh-movement relates to the re-activation of the entry of the moved noun in the semantic lexicon (see Friedmann & Gvion, 2003; Gvion & Friedmann, 2012; Love & Swinney, 1996 for evidence that the re-activation in relative clauses is semantic). The activation may also be linked to operations related to argument structure and the incorporation of the moved element into the argument grid of the verb (Biran & Friedmann, 2012; den-Ouden et al., 2012; Shetreet et al., 2007, 2010).

It is important to note that the activation of temporal regions for wh-movement was bilateral: Wernicke’s area and its right homologue have been identified in many neuroimaging studies of syntactic processing (Ben-Shachar et al., 2003, 2004; Cooke et al., 2001; Dapretto & Bookheimer, 1999; Grodzinsky, 2006; Just et al., 1996). Our study, thus, further confirms the involvement of Broca’s area and bilateral posterior temporal regions in the processing of sentences with wh-movement.

The comparison between topicalized and simple sentences in our study also yielded activation in the right IFG (BA 47), left precentral gyrus, and the left cerebellum. These areas were previously linked to language comprehension (Binder et al., 1997; Cook, Murdoch, Cahill, & Whelan, 2004; Fabbro, Moretti, & Bava, 2000; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008; Kuperberg, Lakshmanan, Caplan, & Holcomb, 2006; Tesnik et al., 2009), but were not found in studies of the processing of wh-movement (Ben Shachar et al.’s 2004 study that tested topicalization used ROI analysis that did not include this specific area.). Indeed, wh-movement-related activations that were found in the right IFG...
were restricted to an area superior to the one found in the current study (Ben Shachar et al.'s, 2004) that tested topicalization used ROI analysis that did not include this specific area. The right IFG (BA 47) has previously been linked to theory of mind and discourse functions (Kobayashi, 2008; Kuperberg et al., 2006; Langleben et al., 2005). The activation of this region in the current study in response to topicalization structures may result from the discourse role of topicalization. A speaker uttering a topicalized sentence thinks about the mental state of the hearer and intends to stress to the hearer the more important or new sense of the sentence. In turn, the hearer needs not only to process the syntactic structure of the topicalized sentence, which involves wh-movement, but also to process the discourse function of topicalization and the communicative intention of the speakers.

In summary, topicalization showed increased activations in the left IFG and bilateral temporal regions, the same brain regions that were previously linked to other structures derived by wh-movement – relative clauses and wh-questions. Because these structures share syntactic, but not semantic/pragmatic features, the source of the activations in the left IFG and the temporal regions is most likely syntactic. Topicalization also results in activations in additional regions, such as the right IFG (BA 47), which are not normally reported with the other syntactic structures derived by wh-movement. Because the right IFG has been linked to theory of mind and discourse processing, it is possible that this region plays a role in pragmatic processes that take place with topicalization but not with relative clauses and wh questions.

4.2. Verb movement

In the comparison of sentences that involve verb movement to the second sentential position and sentences without it (AVSO > ASVO), we found one cluster of activation—in the left IOG/lingual gyrus. In the domain of language, the left IOG is linked to reading and reading dysfunction (e.g., Gaillard, Balsamo, Ibrahim, Sach, & Xu, 2003; Kuriki, Takeuchi, & Hirata, 1998; Shaywitz et al., 2004; You et al., 2011). According to some researchers, these regions play a phonological role: they interface phonology and orthography and play a role in phonological retrieval from visual input (Brem et al., 2010; McCrory, Mechell, Frith, & Price, 2005; Price & Mechelli, 2005; Tan, Laird, Karl, & Fox, 2005). This idea is based on neuroimaging studies where the left occiptotemporal regions showed hyper-activation during the performance of a rhyming task (Burton, Locasto, Krebs-Noble, & Gullapalli, 2005), as well as during phonological decision in individuals with dyslexia (Rumsey, Nace, Donohue, & Wise, 1997), and after phonological training or phonological remediation (Brem et al., 2010; Hashimoto & Sakai, 2004; Sandak et al., 2004; Shaywitz et al., 2004; Small, Flores, & Noll, 1998; Temple et al., 2003). IOG activation was also associated with pseudoword reading (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Frith, Kapur, Friston, Liddle, & Frackowiak, 1995; Petersen, Fox, Snyder, & Raichle, 1990), which requires grapheme-to-phoneme conversion through the phonological route, and phonological assembly in a phonological working memory buffer (Castles, Bates, & Coltheart, 2006; Jackson & Coltheart, 2001).^3

The activation of the left IOG in this study cannot be associated with its role in reading, because all of the stimuli were presented auditorily. However, the phonological role of this area can account for the activation we observed for verb movement. Recent theories of verb movement suggest that the movement of the verb to the second position of the sentence does not take place in narrow syntax, but rather in the phonological component (Chomsky, 1995, 1999, 2001). This component, the phonological form (PF), is assumed to be the level of processing where the sentences are assigned with the phonological representation, after the construction of their syntactic structure (see Neeleman & Reinhart, 1998). These researchers suggest that some word order variations occur at this phonological stage. With regard to verb movement, for example, the syntactic component produces an output that is in the canonical (base-generated) word order, and the verb is placed before the subject only at the phonological stage (Zwart,

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^3 This area has also been connected with semantic processing of objects (e.g., Chao, Haxby, & Martin, 1999; Perani et al., 1999; Tyler et al., 2004). However, the semantic function of this area concerns mainly object processing at the single word level. The conditions in our study included exactly the same words, thus no difference at the single word level is expected between the conditions. Therefore, it is unlikely that the increased activation in the left IOG with the verb movement condition is due to its role in object processing.
2001; see also Friedmann et al., 2013). Such theories can also explain the different activational patterns of 
wh- and verb movements, as each movement type occurs in a different linguistic level: wh-movement occurs at the syntactic level, whereas verb movement occurs at the phonological one.

4.3. Different approaches to noncanonical word orders

In this manuscript, we assumed the analysis of noncanonical word order suggested by the generative syntactic accounts, and specifically, the Minimalist Program (e.g., Chomsky, 1995). This analysis predicts differences between wh-movement and verb movement, and this is what drove us to compare the two structures. Our results, which clearly indicate differential brain activation patterns for wh-movement and verb movement, are naturally accounted for by the generative syntactic theory. Other analyses have also been suggested to account for noncanonical word orders and to predict processing similarities or differences between the two movement types.

Some computational resources and memory-based theories argue that the difficulty to process noncanonical word orders depends on the distances between the relocated element and its original position (e.g., Fedorenko, Woodbury, & Gibson; Grodner & Gibson, 2005; Lewis, Vasishth, & Van Dyke). That is, increasing the distance between the element and its original position would induce greater activations. To the best of our understanding, under such accounts, the distance, but not the movement type, should influence the intensity of the activation. Thus, verb movement and wh-movement sentences are expected to show increased activation compared to canonical sentences in the same brain region. Furthermore, our wh-movement condition, in which the moved element was more distant (i.e., had more words) from their original position, is expected to show increased activation in the same brain region, compared to the verb-movement condition. Our findings were different: the comparison of verb movement structures to the canonical structure showed activations in different brain regions than did the comparison between wh-movement structures and the canonical order. Therefore, approaches that ascribe the two structures to different syntactic properties are better suited to account for the differential activations found in this study.

A similar logic applies for experience-based theories (e.g., Hale, 2001; Levy, 2008; Reali, & Christiansen, 2007). Such accounts assume that frequency of the sentence structure influences its processing, so that more frequent structures are easier to process than the less frequent structures. Unfortunately, structural frequency information is not currently available for Hebrew. However, our results are not likely to be ascribed to different degrees of structural frequency because we would then expect to find activations, possibly with different magnitudes, in the same region for the comparison with the frequent structure. Thus, our results are in line with the generative linguistic, rather than processing-based, explanations for the differences between verb and wh-movements.

Alternative analyses for word order variation have also been suggested within other generative frameworks. Such theories mostly argue for nontransformational analysis of noncanonical word orders, according to which constituents that are placed in noncanonical positions are based-generated in those positions (e.g., Lexical Functional Grammar, Bresnan, 2001, or Head-driven Phrase Structure Grammar, Pollard & Sag, 1994). Within these theories, there is a debate regarding the differences between wh-movement and verb-movement (e.g., Kiss & Wesche, 1991). Our results clearly support those theoretical accounts that suggest different representations for the two movement types.

The differential patterns we found also cannot be ascribed to prosodic differences between the conditions. First and foremost, as reported in the Methods section, there were no pitch differences between the conditions in our study. Additionally, whereas there are sparse reports linking the posterior STG to prosody processing (e.g., Rota et al., 2008; Wildburger, Ackermann, Kreifelts, & Ethofer, 2006), we do not know of any indication that the left IFG is also related to prosody. Thus, it is unlikely that the activations that we found are related to prosody.

4.4. Conclusion

The main result of the present study is the evident distinction between wh-movement and verb movement. Although both movement types generate word orders that diverge from the canonical SVO, there is a clear difference in their cortical processing. Thus, our results clearly support theories within
which *wh*-movement and verb movement belong to two different natural categories, and which can account for the completely different brain activations related to the two types of syntactic movement. One such account is the generative transformational syntactic theory (Chomsky, 1995), which we assume here. In fact, any linguistic and psycholinguistic framework for noncanonical word orders should account for the distinction reported here. The findings of the current study are in line with previous behavioral and neuropsychological results, offering further support for the involvement of Broca’s area (left IFG, BA 44/45) and bilateral posterior regions (including Wernicke’s area) in the processing of *wh*-movement.

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