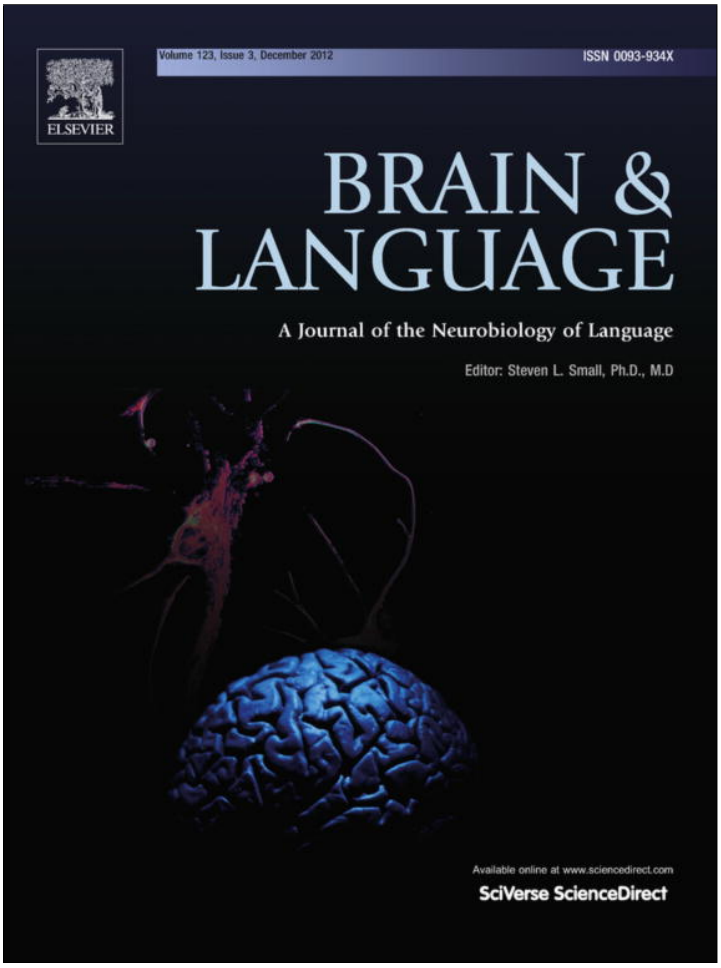
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Distinguishing grammatical constructions with fMRI pattern analysis

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ABSTRACT

All linguistic and psycholinguistic theories aim to provide psychologically valid analyses of particular grammatical patterns and the relationships that hold among them. Until recently, no tools were available to distinguish neural correlates of particular grammatical constructions that shared the same content words, propositional meaning, and degree of surface complexity, such as the dative (e.g., *Sally gave the book to Joe*) and the ditransitive (e.g., *Sally gave Joe a book*). We report the first fMRI data that distinguish such closely related, abstract grammatical patterns. Multi-voxel pattern analysis (MVPA) proved capable of discriminating at above-chance levels between activity patterns arising during reading of dative and ditransitive sentences. Region-of-interest analyses reveal that the union of certain language-relevant areas, anterior and posterior BA22, BA44/45 and BA47, yield classification accuracy above chance and above that of control conditions in the left hemisphere but not in the right. Looking more closely at the LH ROIs, we find that the combination of areas aBA22 and BA47 is sufficient to distinguish the two constructions better than the controls and better than chance. The fact that both of these areas—particularly BA47—have been implicated in semantics, lends support to claims that the two constructions are distinguishable semantically. More generally, the ability to distinguish closely related grammatical constructions using MVPA offers the promise of addressing traditional theoretical questions on a neuroscientifically grounded basis.

1. Introduction

One thing all language researchers agree upon is that a major and so far elusive goal is a psychologically plausible account of our remarkably subtle knowledge of language. Researchers disagree about whether such knowledge involves underlying levels of syntactic representation, whether the knowledge is exemplar based or governed by abstract rules, whether the knowledge involves a modular syntactic system, and where we should expect various aspects of linguistic representations to be neurally represented. Research methods have become much more sophisticated over the years, and large data sets have become much more widely available, and yet these basic debates have continued unabated.

Certain questions hinge on how linguistic constructions are represented, and the issue of whether or how one construction is related to another. *Argument structure constructions*, for example, the ditransitive (in a) and the dative (in b), provide the basic clause structures of a language and the fundamental means by which speakers convey who did what to whom (Goldberg, 1995).[1]

a. Jessica sold Mike a hot dog (ditransitive)
b. Jessica sold a hot dog to Mike (dative)

The analysis of argument structure patterns has formed the cornerstone of virtually every linguistic theory for the past four or five decades (Bresnan, 1982; Chomsky, 1965; Goldberg, 1995; Hudson, 1990; Jackendoff, 1990; Lakoff, 1970; Langacker, 1987; Pollard & Sag, 1987). Theories that posit underlying structures in which words in a sentence move in an elaborate syntactic tree before they are available for pronunciation predict that certain pairs of argument structure constructions, such as the dative and ditransitive, have equivalent semantics insofar as one is assumed to be derived from the other (Baker, 1996; Hale & Keyser, 1997; Larson, 1988; cf. also Bresnan, 2010), and derivations are assumed to preserve meaning (Partee, 1970). On the other hand, other theorists have argued that the two constructions have subtly distinct semantics, in that each conveys a slightly different construal of the same event (Ambridge et al., 2012; Goldberg, 2002; Kay, 2000; Pinker, 1989). The latter view is supported by the fact that sentences such as those in (a and b) are instances of two larger generalizations having to do with transfer and caused-motion, respectively (Table 1).

A prerequisite to exploring these issues at the neural level is to determine that the representations of individual constructions can be distinguished at all, when propositional meaning and content

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[1] Constructional terminology is used here, but the research can naturally be construed as an investigation into the neural representation of combinations of linking rules (Dowty, 1991; Jackendoff, 1987; Pinker, 1989) or lexical templates (Rappaport Hovav & Levin, 1998).

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Table 1
The Ditransitive and Dative/“caused motion” constructions with examples.

Construction	Meaning	Form	Construction	Meaning	Form
Ditransitive	Intended transfer	NP V NP NP	Dative/caused motion	Caused motion	NP V NP $\text{PP}_{\text{location}}$
She threw him something			She threw something to him		
She baked him something			She threw something toward him		
She offered him something			She pushed something on him		
She made him something			She put something on him		

words are controlled for, as they are in (a and b). Moreover, the ditransitive and dative constructions have the same number of arguments, the same surface complexity, and both are often used for the same general purposes. In addition, as discussed in the methods section, the frequencies of the two constructions do not differ significantly from each other.

At the same time, the dative and the ditransitive are clearly distinguishable in principle, although different theorists have distinct views of exactly how. As just noted, many have argued that the ditransitive construction is systematically associated with the meaning of “transfer,” while the dative is more generally associated with “caused-motion” (Goldberg, 1995; Oehrle, 1974; Pinker, 1989). The two constructions are also typically used in slightly different discourse contexts (Bresnan, 2007; Erteschik-Shir & Lappin, 1979; Rappaport Hovav & Levin, 2005; Thompson, 1995). In addition, most theorists agree that the two constructions differ syntactically in that only the dative has a prepositional phrase, although even this is not completely uncontroversial, as Larson (1988) has argued that the ditransitive has an (invisible) preposition as well. Clearly, the distinction must be represented neurally in some way. And yet given the basic commonalities of these constructions, they are highly likely to be represented, produced, and comprehended in the same area(s) of the brain on the same time scale, rendering more traditional univariate designs—designs that seek to detect differences in overall neural activation within relatively large-scale brain structures—likely to be largely impotent.[2]

Fortunately, there exist new tools that allow us to distinguish very closely related pairs of stimuli. In fact, certain new techniques that have already been employed to study phonology and semantics hold particular promise. In a move away from designs that compare tasks that involve a general type of processing to those that do not (e.g., tasks that involve “phonological” processing with tasks that do not), multi-voxel pattern analyses (MVPA) allows us to use multivariate “qualitative” designs that can distinguish between items within a given domain (Haynes & Rees, 2006; Pereira, Mitchell, & Botvinick, 2009; Polyn, Detre, & Haxby, 2006), by exposing a simple machine-learning classifier system to fMRI data in the form of vectors composed of voxel activations across a given area or areas. Such pattern analysis methods have already been used to distinguish between individual phonological representations (Botvinick & Bylsma, 2005; Formisano, Martino, Bonte, & Goebel, 2008), and between individual conceptual or semantic representations (Mahon & Caramazza, 2010; Weber, Thompson-Schill, Osherson, Haxby, & Parsons, 2009). The present study is the first to apply these same methods to distinguish individual grammatical patterns. In particular, we used multi-voxel analysis to discriminate between activation patterns induced by the processing of dative and ditransitive constructions.

Our main question is whether fMRI pattern analysis can distinguish between grammatical structures closely matched in content and surface complexity, when lexical items, frequency, and discourse context are controlled for.

An additional point of interest is whether pattern analysis might shed some new light on where grammatical structure is represented in the brain. Our understanding of the functional neuroanatomy underlying language currently recognizes a network of language-relevant areas (e.g., Grodzinsky & Friederici, 2006; Kaan & Swaab, 2002; Osterhout, Kim, & Kuperberg, 2007; Stowe, Haverkort, & Zwarts, 2005). In addition to left BA44/45 (Broca’s area) and left posterior BA22 (Wernicke’s area, although cf. Bogen & Bogen, 1974), the anterior portion of LH Brodmann’s area 22 and LH BA47 have been implicated as relevant to the processing of simple grammatical patterns (e.g., Bates et al., 2003; Brennan et al., 2012; Dronkers, Wilkins, Valin, Redfern, & Jaeger, 2004; Grodzinsky & Friederici, 2006; Hagoort, 2005).[3] In the present study, we focused on the contribution of these areas in order to determine whether we can distinguish between two highly similar constructions using MVPA. See Fig. 3.

We separately analyzed the same areas in the right hemisphere to determine whether any discrimination was lateralized. While the left hemisphere is typically more dominant for language (Gazzaniga, 1983; Vigneau et al., 2006), a growing number of studies have found the right hemisphere to be implicated as well (for overviews, cf. Federmeier et al., 2007; Jung-Beeman, 2005). Classification was carried out on all voxels within the tested areas.

2. Methods

2.1. Participants

Twenty adults (mean age: 21.3 ± 2.9 years; 10 females) with no neurological impairments participated in exchange for course credit or a nominal payment. All participants provided informed consent, with all procedures approved by the Princeton University institutional review board.

2.2. Procedure

Within each trial of the experimental task, participants were expected to read three sentences, presented in succession, each for 2 s. All three sentences appearing within the same trial shared either dative or ditransitive structure. Participants witnessed 56 such trials, half of which were datives and half of which were ditransitives with trials presented in random order. Each dative sentence had a corresponding ditransitive sentence that shared the same content words. Proper names were used for all human arguments and no discourse context was given, so the information structure difference between the two constructions was minimized. For a list of stimuli, see Appendix.

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[2] Recent work by Christensen and Wallentin (2011) has found more activation in Left BA 45 for one of another pair of near synonyms in Dutch. In particular, they found that instances of the ‘container-theme’construction (e.g., “Jack sprayed the wall with paint”) evoke more LIFG activation than the ‘theme-container’ construction, (e.g., “Jack sprayed paint on the wall”). As the authors suggest, the difference in this case may be one of general complexity. In English at least, the ‘container-theme’ construction is markedly less frequent than the ‘theme-container’ construction. In line with this idea is the fact response times to this construction were slower when the verbs used allowed either construction.

[3] In response to a reviewer’s suggestion, we subsequently considered the contribution of posterior STS extending into BA 39, since this area has also been found to be relevant to the comprehension of simple sentences (Grewe et al. 2007; Newhart et al. in press; Thothathiri, Kimberg, & Schwartz, 2012). It turns out this area did not distinguish the two constructions (see note 4).

A search of the 425 million word on-line Corpus of Contemporary American English was performed to search for strings containing each verb in the dative (V [a N] [to NP]) or the ditransitive (V [NP] [a N]) as used in our stimuli. Results revealed that the frequencies of the two constructions are not significantly different from one another, χ^2 (1,657,842) = 1.95, $p = 0.1626$.

To encourage encoding of both form and content, each trial ended with a probe sentence calling for a three-way choice: Participants selected among three buttons to indicate (1) the probe exactly replicated one of the three foregoing stimulus sentences, (2) the probe was similar in meaning but not matched word-for-word with one of the stimuli, or (3) neither. Probe sentences that were intended to elicit the second category of response matched one of the preceding stimuli except for a shift from dative to ditransitive structure (or vice versa).

Note that dative sentences contain the word *to* and are thus two characters longer than ditransitives. Any classification found between datives and ditransitives could potentially arise as a result of this distinction. Thus two control conditions were included. These were scrambled word lists of the dative or ditransitive forms of each sentence. For the example sentences (a and b) in the introduction, the matched control conditions were '*sold, Mike, hot dog, Jessica, to, a*' and '*Jessica, hot dog, sold, Mike, a*' respectively. We reasoned that any brain areas showing differences between the sentences and not the control conditions could thus only be attributed to differences in the grammatical constructions.

The control conditions were generated by scrambling either dative sentences (the dative-control) or ditransitive sentences (the ditransitive-control) to create lists of words, with each word separated by a comma. The word lists were integrated into a task very similar to the main experimental task. On each trial, participants again viewed a series of three word lists. Following presentation of three stimuli from the dative control or the ditransitive control, participants saw a probe word calling for a three-way choice: Did the probe (1) exactly match a word occurring somewhere within the three preceding lists of words, (2) share a similar meaning with a word that had occurred, or (3) neither.

The experiment comprised eight scanner runs, each containing seven randomly ordered trials of each task. A central fixation cross appeared for 7.53 s (3 TRs) between adjacent trials. Over the course of the study, equal numbers of dative and ditransitive trial-types were presented, in both experimental and control tasks, and approximately the same number of trials had responses (1), (2) and (3). Prior to scanning, participants practiced the task in a design equivalent to that in a single scanner run.

2.3. Image acquisition and analysis

All data was collected on a 3 Tesla Siemens Allegra, head-only scanner at Princeton University. Functional data included four runs of a standard echo planar imaging (EPI) sequence, each consisting of 28 trials (7 from each condition) to give a total of 205 volumes, with a TR of 2.51 s and a TE of 30 ms. Data resolution varied between subjects with seven subjects having 28×1.8 mm oblique slices and a field of view (of 24 mm) with 128×96 voxels, covering an area which included all regions of interest, and all other subjects having 34×2.5 mm slices which covered the whole brain volume. Of those with 34 slices, 7 had a field of view matrix size of 128×128 and 3 had a field of view with 128×96 voxels). The variation in voxel size was an attempt to see whether higher resolution data would improve classification, however no effect of resolution on classifiability was found.

The data were preprocessed with AFNI (Cox, 1996), undergoing the steps of despiking, slice acquisition timing correction, motion correction, quadratic detrending and normalization of each voxel to percent change relative to its mean during each run. The first five images in each run were discarded.

A General Linear Model was fit using the "3dDeconvolve" function in AFNI, using one regressor for each of the four conditions, as well as six regressors containing motion correction parameters, for each subject. We tested two contrasts, dative minus ditransitive, and dative-control minus ditransitive-control, paired across subjects. We did not expect this univariate analysis to yield any regions with significant differences in activation for either contrast.

For MVPA analysis, a General Linear Model was fit using the "3dDeconvolve" function in AFNI, using separate regressors for the stimuli in each trial and the responses in each trial, as well as six regressors containing motion correction parameters, for each subject. Each trial was thus modeled as a separate regressor, with an event lasting for the 6 s during which the three sentences were presented. This yielded one brain image of regression coefficients per trial, belonging to one of the four experimental conditions: dative, ditransitive, dative-control or ditransitive-control.

Each trial brain image became an example for MVPA analyses, with a total of 28 examples from each condition. The two classification problems considered were distinguishing dative from ditransitive, and distinguishing the dative-control (lists of words) from the ditransitive-control (lists of words).

For each of these tasks we performed a cross-validation loop leaving out two examples at a time (one from each condition), training a classifier on the remaining examples and testing it on those left out. At the end of the cross-validation procedure we had a prediction for each example used as a test set.

In each cross-validation iteration, we selected voxels and trained a linear SVM classifier (Chang & Lin, 2001) with the default parameter settings on the chosen subset. (Voxel selection is a standard step in MVPA that narrows down the set of voxels analyzed, focusing in on voxels that discriminate most strongly between target classes. Selection occurs within a training set, with an independent testing set held out, so no circularity or bias is introduced into the final classification analysis. Voxel selection is typically necessary, as MRI yields a feature set – i.e., set of voxels – much larger than the set of training and testing examples, a situation that makes it extremely easy to 'overfit' training data, undermining generalization to unseen test data.) As a first voxel selection measure, we began by identifying a large set of active voxels in the training set, the union of the 8000 voxels with the highest regression coefficients in each condition. The number 8000 was chosen so as to ensure that at least 2% of all voxels would survive the second stage of voxel selection, described below. As a further voxel-selection measure, we performed a Recursive Feature Elimination procedure (RFE, as described in De Martino et al., 2008) for 10 cycles. Each cycle consisted of a second cross-validation loop within the training set, where a linear SVM was trained and voxels were ranked by the magnitude of the corresponding weight in the classifier, with the bottom 30% being discarded and the rest used in the following cycle. At the end of the process we were left with $\sim$450 voxels, which were used to train the final classifier that was applied to the test set.

The classification accuracy in each of the two tasks was calculated as the fraction of examples which had their conditions predicted correctly by the classifier. Accuracy significance was computed under the null hypothesis that the classifier extracted no information from the data and thus performed at random. The number of correctly labeled examples would thus have a binomial distribution with probability 0.5 and 56 trials (Pereira et al., 2009), and the right tail of this distribution will give us the threshold for a given significance level (we used 0.05). This produced two p-values per subject, one for each classification task. Classification accuracy between the two tasks was compared using a two-tailed paired t-test.

A set of exploratory follow-up analyses tested whether classification accuracy was better for sentences (dative/ditransitive) than lists of words (dative-control/ditransitive-control) within a set of regions of interest (ROI). Sentence classification accuracy was tested against chance in each Brodmann-area ROIas described in the results, in order to bolster power for detecting a significant difference between sentence and control-stimulus classification, we tested for this difference after aggregating across ROIs that showed a statistically significant difference from chance on sentence classification. Note that because this procedure admitted areas showing classification either above or below chance, it did not bias toward a positive experimental–control difference. These analyses focused on data for participants whose whole-brain classification results were significant at the 0.05 level for *either* the dative/ditransitive or dative-control/ditransitive-control tasks (note that using this criterion avoided circularity, insofar as it did not favor participants for whom the former classification was more accurate than the latter). The first step in the ROI analysis was warping all subjects to match a common template (TTN27) using the @auto_tlrc function from AFNI. The ROIs considered were Broca's area (left BA44 and 45), Wernicke's area (left posterior BA22), left anterior BA22, and left BA47; they were defined using the AFNI Talairach atlas. The corresponding ROIs in the right hemisphere were analyzed separately. We then trained linear SVM classifiers for both tasks in each ROI, using all voxels contained within it, for each subject (again with default parameter settings).

3. Results

3.1. MVPA analysis

On whole-brain MVPA analysis, the dative and the ditransitive were distinguished at levels significantly above chance (mean 61.7%, sign test, $p < 0.0005$). In contrast, classification accuracy for lists of words (dative-control vs. ditransitive-control) did not differ significantly from chance levels (mean 53.7%, sign test, $p > 0.05$). Sentence classification was significantly higher than control classification (paired *t*-test, $p < 0.005$; Fig. 1).

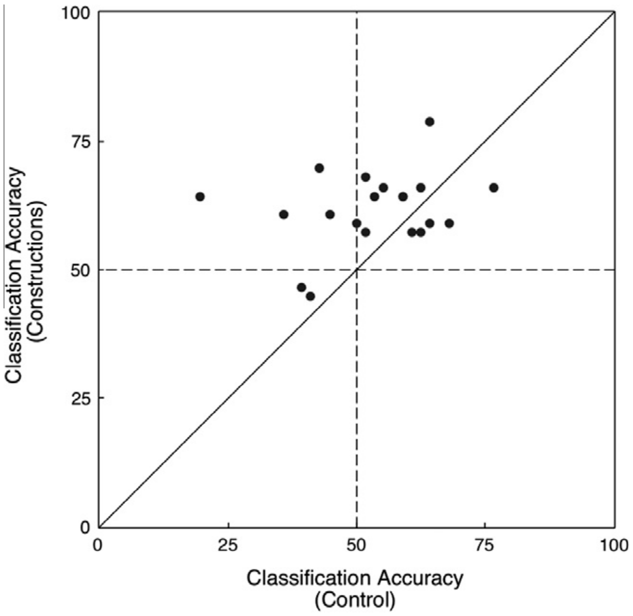

Fig. 1. Individual-subject, whole-brain classification accuracies for constructions (dative vs. ditransitive) and lists of words (dative-control vs. ditransitive-control).

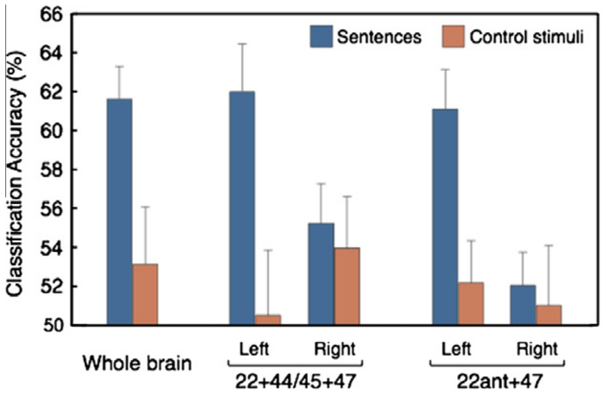

Fig. 2. Classification results within the whole brain, the union of all ROIs of interest (complete BA22 + BA47 + BA44/45), and the union of aBA22 + 47 in the left and right hemispheres. Bars indicate standard error.

Thirteen subjects yielded above-chance classification for either sentences or for lists of words, and so these 13 were included in follow-up ROI analyses. As planned, classification accuracy was evaluated within left and right anterior and posterior BA22, BA47, and BA44/45.

When these language-relevant areas are combined in the left hemisphere, they yield classification accuracy of 61.10%, which is above chance ($p < 0.001$) and above that of control conditions ($p = 0.01$). Importantly, these combined areas were unable to reliably distinguish between the two control conditions: ($p = 0.88$); this demonstrates that the distinction in the experimental conditions was not due simply to detecting the word "to" or to the addition of a single morpheme in the dative.

The union of corresponding areas in the RH yielded classification accuracy above chance for the experimental conditions as well ($p = 0.02$), but the contrast with the control condition did not approach significance ($p = 0.70$).

Considering individual ROIs in the LH, results reveal that anterior BA22, and BA47 were each sufficient to distinguish the two constructions with above-chance accuracy (2-tailed *t*-tests: $p < 0.001$, $p = 0.02$, respectively). These areas were not able to reliably distinguish between the two control conditions: dative/ditransive vs. dative-control/ditransitive-control, ($p = 0.38$ and $p = 0.57$ respectively). Although the difference in classification accuracy when compared with the controls did not reach statistical significance within these individual ROIs, when classification was based on the combination of the two ROIs, dative/ditransitive discrimination was found to be significantly better than dative-control/ditransitive-control discrimination ($p = 0.03$; Fig. 2).

In fact, the whole brain classification was not significantly better than the combination of LH aBA22 and LH BA47 ($p = 0.135$). Neither LH BA44/45 nor LH posterior BA22 were able to distinguish the two constructions from chance on their own ($p = 0.08$ $p = 0.72$, respectively); nor were they able to distinguish the two control conditions ($p = 0.64$ $p = 0.27$, respectively). None of the individual areas in the RH yielded significant discrimination of the two constructions (aBA22 $p = 0.14$; pBA22 $p = 0.59$; BA44/45 $p = 0.08$; BA47 $p = 0.21$), nor the control conditions (aBA22 $p = 0.06$; pBA22 $p = 0.39$; BA44/45 $p = 0.21$; BA47 $p = 0.20$).

Comparing RH and LH directly in Brodmann areas 22 + 44/45 + 47, we find a significant difference between sentence classification (2-tailed *t*-test, $p = 0.044$). Comparing RH and LH directly in just areas aBA22 + BA47, we also find a significant difference $p = 0.001$.[4]

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[4] At the request of a reviewer, we subsequently analyzed LH posterior STS extending into BA 39, using a cub file used as a mask that was generously provided by Malathi Thotharhiri. It turns out that this area does not distinguish our constructions nor the control conditions at above chance levels (classification accuracy for constructions: $M = 52.14$ SD: 9.57; for controls: $M = 54.73$ SD: 11.12).

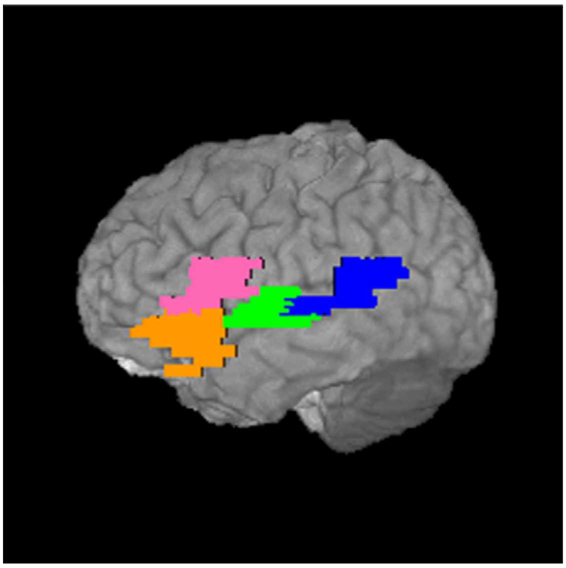

Fig. 3. Brodmann's areas 47 (orange); 44/45, Broca's area (pink); anterior 22 (green), posterior 22 (blue).

3.2. Behavioral results

If performance in the ditransitive and dative conditions were significantly different, it would be conceivable that any differences detected during exposure could be due to differences in preparation for the task trials. However, performance accuracy did not differ ($M = 16.53$ vs. 16.37; 2-tailed paired t-test, $p = 0.8192$), nor did reaction times ($M = 2.3764$ vs. $M = 2.4663$; $p = 0.2747$). This fact further supports the idea that the two constructions do not differ in terms of complexity.

3.3. Univariate analysis

GLM analysis of the experimental conditions (sentences) vs. baseline finds large areas of significant activation including temporal, frontal and occipital areas as evident in Fig. 4. Much of the activation pattern is in line with previous studies of sentence processing (e.g., Kaan & Swaab, 2002; Osterhout et al., 2007; Stowe et al., 2005), with occipital activation likely due to the fact that our stimuli were presented visually. As expected, areas including LH BA22 and LH BA44/45 show increased activation. BA47 and frontal networks were deactivated in the sentence condition compared to the baseline. As with all GLM analyses in this paper, GLM was performed with alpha = 0.05 and significant clusters identified using alphasim in afni (Ward, 2000).

Results demonstrate that univariate GLM analysis was not adequate to distinguish the dative and the ditransitive constructions when data from the whole brain was used, nor when the particular ROI of interest, LH aBA22 + BA47 was considered. Behavioral results also do not distinguish the two constructions. GLM analyses are designed to detect quantitative differences, and RT measures are normally sensitive to quantitative differences as well. The fact that neither measure detected a difference between the two constructions suggests that the difference found using MVPA is not simply due to the quantity of processing resources involved.

4. Discussion

We set out to determine whether two grammatical constructions, the dative and the ditransitive, could be distinguished at all using fMRI data, given that they convey the same propositional content and were both presented in active, declarative form. The most striking result is that they can be; that is, sets of ditransitives such as *Jessica sold Mike a hot dog* and *Joe awarded Liz a ribbon* are distinguishable from sets of datives such as *Jessica sold a hot dog to Mike and Joe awarded a ribbon to Liz.* Note that, as in these examples, identical lexical items were used in stimulus sentences in both of the experimental conditions, and lexical items varied across the stimuli within the same condition. Thus, the generalization that is detected is untethered to specific words. The fact that the scrambled word lists in the dative-control and ditransitive-control could *not* be distinguished by the same classifier makes unlikely any explanation that relies on a simple *to* detector, or a discrimination based on overall length in terms of syllables or morphemes. The fact that neither the GLM data nor the behavioral distinguishes the two constructions suggests further that the MVPA analysis is not based simply on one or the other construction being more complex or more strongly engaging some broad form of processing, but is instead detecting a qualitative difference between the two constructions. Thus the findings demonstrate that individual abstract constructions can be distinguished using fMRI data, even when content, open-class words, complexity, and frequency are held constant.

The ability to distinguish the two constructions was significant, but absolute classification accuracy was far from ceiling as it did not reach much beyond 60%. This is perhaps to be expected since the ability to distinguish the two strikingly similar constructions

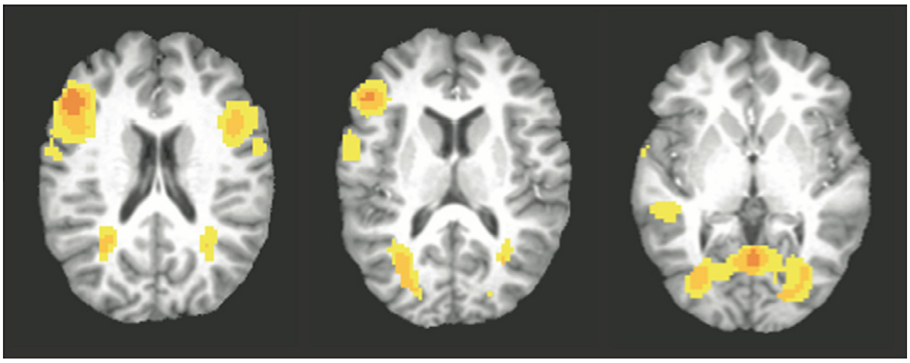

Fig. 4. GLM analysis of sentence condition – rest. Activation includes areas in BA22, and BA44/45. BA47 showed deactivation (not pictured) to the sentence condition – rest (alpha = 0.05).

with fMRI data is akin to being able to distinguish an African elephant from an Asian elephant, or a teaspoon from a soupspoon. MVPA is useful in precisely these types of low contrast situations, with previous findings of 60–70% accuracy being the norm in studies that undertook to make similarly fine discriminations (e.g., Formisano et al., 2008; Soon, Brass, Heinze, & Haynes, 2008). Nonetheless, in future work it will be useful to employ a functional localizer in order to allow for subtle individual variations in the language-relevant network, which should provide greater power to detect distinctions (cf. Fedorenko et al., 2012; Fedorenko & Kanwisher, 2009).

The fact that the classifier was able to distinguish the sentences better than control stimuli in the LH and not the RH mirrors the dominance of the LH in language processing (Gazzaniga, 1983). Moreover, there exists precedent for implicating anterior BA22 and BA47 in the general processing of argument structure constructions. Bates et al. (2003) and Dronkers et al. (2004) found the same areas (as well as BA39 and 46) to be relevant to the comprehension of simple sentences, using voxel-based lesion-symptom mapping with stroke patients.

While the information in any one tested area alone is either insufficient or too noisy for the classifier to significantly discriminate better than the controls, our data demonstrate that information from a combination of areas does provide better discrimination of the two constructions. Interestingly both areas, and particularly BA47, have been implicated in semantics. Left anterior BA22 is active in conceptual combination (Baron, Thompson-Schill, Weber, & Osherson, 2010), and sentence-level semantic integration (Brennan & Pylkkänen, 2012; Noppeney & Price, 2004; Stowe et al., 2005; Vandenberghe, Nobre, & Price, 2002). The area also appears to be involved in the semantics of single words or concepts, as it has been implicated in picture naming and word comprehension in both typical populations (Pobric, Jefferies, and Lambon Ralph, 2007) and in patient populations (Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004).

The same area has also been implicated in processes that are often assumed to be syntactic. For example, Mazoyer et al. (1993) found more anterior BA22 activity when Jabberwocky type sentences—i.e., sentences with nonsense words replacing all open class words—were witnessed as compared with periods of rest. Dronkers et al., 2004 likewise implicated this area in the processing of morphosyntax during sentence comprehension (cf. also Hagoort, 2005; Humphries, Binder, Medler, & Liebenthal, 2006). Whether these processes are in fact purely syntactic is not entirely clear. There is evidence that both Jabberwocky type sentences and morphosyntax convey meaning (Bolinger, 1977; Johnson and Goldberg, 2012; Kako, 2006; Langacker, 1987). Obleser, Meyer and Friederici (2011) implicate increased activation in aBA22 during more noisy, syntactically complex input, which could be due to an increased reliance on semantics when other cues are less reliable or accessible for determining who did what to whom. These findings indicate that aBA22 is involved in the combination of elements. In fact, the area is also active in the generation of melodies (Brown, Martinez, & Parsons, 2006), possibly because melodies, like language, often have certain combinatorial structure (Jackendoff, 1983; Koelsch & Siebel, 2005; Maess, Koelsch, Gunter, & Friederici, 2001; Patel, 2003).

Left hemisphere BA47 has been invoked as crucial for the interpretation and composition of meaning (Booth et al., 2002; Dapretto & Bookheimer, 1999; Gabrieli, Poldrack, & Desmond, 1998; Hagoort, 2005; Poldrack et al., 1999). The required processing may well be domain-general, as Wagner and colleagues have argued that the left ventrolateral prefrontal cortex (including BA47) is involved in semantic integration processes of both words and pictures (e.g., Badre & Wagner, 2002; Wagner, Desmond, Demb, Glover, & Gabrieli, 1997). Levitin and Menon (2003) likewise find that BA47 is involved in musical composition. They state, "...a large body of evidence is now converging to suggest that BA47 ...constitutes a modality-independent brain area that organizes structural units in the perceptual stream to create larger, meaningful representation. That is, it may be part of a neural network for perceptual organization, obeying the rules of how objects in the distal world 'go together' when they are manifested as patterns unfolding in a structured way over time."

It should be noted that areas related to language comprehension are likely quite distributed and redundant, insofar as damage to a single area often does not noticeably affect comprehension. For example, Kho et al. (2008) has found that surgical resection of aBA22 leaves comprehension intact; damage to aBA22 in the case of dementia likewise typically does not affect comprehension until late in the disease (Breedin & Saffran, 1999; Ogar et al., 2011; Rochon, Kavé, Cupit, Jokel, & Winocur, 2004). We are therefore not claiming that LH BA47 and aBA22 are necessary for the comprehension of argument structure constructions, only that they are jointly sufficient to distinguish the two closely related constructions analyzed here. We are also not claiming that no other area or combination of areas would be sufficient to distinguish the two constructions, as other areas are likely to be additionally involved given the distributed nature of comprehension.

Nonetheless, the present findings lend support to theoretical arguments that the dative and the ditransitive constructions differ in semantics as well as syntax, insofar as the areas involved, particularly BA47, are strongly associated with semantics. Arguably, the ditransitive is construed to mean "transfer" whereas the dative conveys (potentially metaphorical) "caused-motion." A result of this difference is that only the ditransitive requires transfer to an entity that is construed to be animate. Despite the fact that this constraint was obscured in our stimuli in that all items included animate recipients, it seems there remains a subtle difference in construal between "someone causes someone else to receive something" and "someone causes something to move into the possession of someone else."

It is possible that the distinction between the two constructions is not based on static representations but instead, more dynamic parsing. But the areas that are able to distinguish the two constructions suggest that what is involved is not purely syntactic parsing, but rather the combination of meaningful elements.

Regardless of the interpretation of the particular ROIs involved, the present findings clearly suggest a method whereby the neural representations of individual grammatical patterns can be explored: multivariate qualitative analyses can be successfully applied to individual constructions. Since the analyses of such patterns have been the subject of heated debates and much theorizing within linguistics and beyond, the technique offers the possibility of a much stronger empirical foundation than we have had to date.

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Appendix A. Stimuli used in each condition in two out of four functional runs

Functional Run 1

Dative sentences	Ditransitive sentences
'Mike brought a book to Chris.'	'Mike brought Chris a book.'
'Liz emailed a response to Jessica.'	'Liz emailed Jessica a response.'
'Matt assigned a topic to Heather.'	'Matt assigned Heather a topic.'
'Steph mailed a gift card to Rob.'	'Steph mailed Rob a gift card.'
'John guaranteed a position to Josh.'	'John guaranteed Josh a position.'
'David slipped a note to Nicole.'	'David slipped Nicole a note.'
'Megan faxed a memo to Dan.'	Megan faxed Dan a memo.'
'Josh rented a surfboard to Chris.'	'Josh rented Chris a surfboard.'
'Rob told a story to Ashley.'	'Rob told Ashley a story.'
'Sarah brought a cake to Steph.'	'Sarah brought Steph a cake.'
'Joe awarded a ribbon to Liz.'	'Joe awarded Liz a ribbon.'
'Heather showed a painting to Amanda.'	'Heather showed Amanda a painting.'
'James emailed a document to Matt.'	'James emailed Matt a document.'
'Josh took a notebook to David.'	'Josh took David a notebook.'
'Jessica sold a hot dog to Mike.'	'Jessica sold Mike a hot dog.'
'Nicole wrote a letter to John.'	'Nicole wrote John a letter.'
'Jen served a volleyball to Megan.'	'Jen served Megan a volleyball.'
'Mike leased a truck to James.'	'Mike leased James a truck.'
'Jen tossed a pencil to Sarah.'	'Jen tossed Sarah a pencil.'
'Amanda served some food to Joe.'	'Amanda served Joe some food.'
'Dan passed a calculator to Ashley.'	'Dan passed Ashley a calculator.'
'book, brought, Mike, to, a, Chris'	'a, Mike, book, brought, Chris'
'emailed, Liz, Jessica, to, response, a'	'Jessica, response, a, Liz, emailed'
'Matt, a, to, assigned, topic, Heather'	'assigned, Heather, topic, Matt, a'
'gift card, mailed, Rob, a, Steph, to'	'gift card, a, mailed, Rob, Steph'
'position, to, guaranteed, a, Josh, John'	'Josh, position, John, a, guaranteed'
'a, Nicole, note, to, slipped, David'	'note, a, Nicole, slipped, David'
'a, to, memo, faxed, Megan, Dan'	'faxed, Megan, Dan, memo, a'
'rented, Chris, to, surfboard, a, Josh'	'surfboard, Chris, a, Josh, rented'
'Ashley, story, told, Rob, to, a'	'Ashley, story, told, a, Rob'
'a, to, cake, Steph, Sarah, brought'	'brought, Sarah, a, Steph, cake'
'Liz, Joe, a, awarded, to, ribbon'	'ribbon, Liz, a, awarded, Joe'
'Amanda, painting, showed, to, a, Heather'	'Heather, Amanda, painting, a, showed'
'document, Matt, to, emailed, James, a'	'a, emailed, Matt, document, James'
'notebook, David, to, a, took, Josh'	'notebook, a, took, David, Josh'
'sold, Mike, hot dog, Jessica, to, a'	'Jessica, hot dog, sold, Mike, a'
'to, letter, a, wrote, Nicole, John'	'letter, a, John, Nicole, wrote'
'a, Megan, Jen, volleyball, served, to'	'served, Megan, volleyball, a, Jen'
'leased, Mike, to, truck, a, James'	'truck, James, leased, a, Mike'
'to, pencil, tossed, Sarah, a, Jen'	'a, tossed, pencil, Sarah, Jen'
'food, some, Joe, to, served, Amanda'	'food, Joe, some, served, Amanda'
'Ashley, Dan, calculator, a, to, passed'	'Dan, Ashley, calculator, a, passed'

Functional Run 2

'Rob sent a package to Steph.'	'Rob sent Steph a package.'
'Jen read a quotation to Chris.'	'Jen read Chris a quotation.'
'Matt threw a frisbee to Nicole.'	'Matt threw Nicole a frisbee.'
'Dan gave a calendar to Mike.'	'Dan gave Mike a calendar.'
'Liz offered a job to James.'	'Liz offered James a job.'
'Ashley sold a house to David.'	'Ashley sold David a house.'
'Heather kicked a ball to Liz.'	'Heather kicked Liz a ball.'
'Nicole wrote a note to Josh.'	'Nicole wrote Josh a note.'
'Mike smuggled a cigar to John.'	'Mike smuggled John a cigar.'
'Joe flicked a paper football to Megan.'	'Joe flicked Megan a paper football.'
'David lowered a rope to Dan.'	'David lowered Dan a rope.'
'Chris served a cocktail to Rob.'	'Chris served Rob a cocktail.'
'Sarah faxed a worksheet to Matt.'	'Sarah faxed Matt a worksheet.'
'Jessica offered a promotion to Amanda.'	'Jessica offered Amanda a promotion.'
'Steph gave a mattress to Ashley.'	'Steph gave Ashley a mattress.'
'James assigned a locker to Heather.'	'James assigned Heather a locker.'
'John lobbed a tennis ball to Jessica.'	'John lobbed Jessica a tennis ball.'
'Megan sent a present to Joe.'	'Megan sent Joe a present.'
'Chris awarded a prize to Jessica.'	'Chris awarded Jessica a prize.'
'Josh promised a raise to Sarah.'	'Josh promised Sarah a raise.'
'Amanda shipped a parcel to Jen.'	'Amanda shipped Jen a parcel.'
'to, package, sent, Rob, a, Steph'	'a, package, Steph, Rob, sent'
'quotation, a, read, Chris, to, Jen'	'Chris, a, read, Jen, quotation'

Appendix A (*continued*)

Functional Run 2	
'Nicole, Matt, to, frisbee, a, threw'	'frisbee, a, threw, Matt, Nicole'
'calendar, Mike, to, Dan, a, gave'	'Mike, Dan, calendar, gave, a'
'a, offered, James, a, Liz, job'	'job, offered, Dan, a, Mike'
'David, Ashley, house, a, sold, to'	'house, David, a, sold, Ashley'
'to, kicked, ball, Liz, a, Heather'	'a, Liz, ball, Heather, kicked'
'Josh, note, wrote, a, Nicole, to'	'Josh, Nicole, a, wrote, note'
'a, smuggled, Mike, cigar, John, to'	'smuggled, John, cigar, Mike, a'
'paper football, Joe, to, a, flicked, Megan'	'paper football, Mega, flicked, a, John'
'rope, Dan, to, lowered, a, David'	'rope, David, a, Dan, lowered'
'Rob, cocktail, served, Chris, a, to'	'Rob, Chris, a, served, cocktail'
'faxed, to, Sarah, worksheet, Matt, a'	'a, faxed, worksheet, Matt, Sarah'
'promotion, offered, a, Jessica, Amanda, to'	'promotion, a, Amanda, Jessica, offered'
'to, gave, a, Steph, mattress, Ashley'	'Ashley, mattress, a, gave, Steph'
'locker, a, James, Heather, assigned, to'	'Heather, James, locker, a, assigned'
'Jessica, lobbed, tennis ball, a, John, to'	'lobbed, tennis ball, Jessica, a, John'
'sent, to, present, a, Megan, Joe'	'a, sent, Joe, present, Megan'
'prize, Jessica, to, Chris, a, awarded'	'prize, awarded, Jessica, Chris, a'
'Sarah, promised, Josh, raise, a, to'	'a, Sarah, promised, Josh, raise'
'parcel, Amanda, Jen, shipped, to, a'	'parcel, shipped, a, Jen, Amanda'

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