

Using Complement Coercion to Understand the Neural Basis of Semantic Composition: Evidence from an fMRI Study

E. Matthew Husband, Lisa A. Kelly, and David C. Zhu

Abstract

■ Previous research regarding the neural basis of semantic composition has relied heavily on violation paradigms, which often compare implausible sentences that violate world knowledge to plausible sentences that do not violate world knowledge. This comparison is problematic as it may involve extralinguistic operations such as contextual repair and processes that ultimately lead to the rejection of an anomalous sentence, and these processes may not be part of the core language system. Also, it is unclear if violations of world knowledge actually affect the linguistic operations for semantic composition. Here, we compared two types of sentences that were grammatical, plausible, and acceptable and differed only in the number of semantic operations required for comprehension without the confound of implausible sentences.

Specifically, we compared complement coercion sentences (*the novelist began the book*), which require an extra compositional operation to arrive at their meaning, to control sentences (*the novelist wrote the book*), which do not have this extra compositional operation, and found that the neural response to complement coercion sentences activated Brodmann's area 45 in the left inferior frontal gyrus more than control sentences. Furthermore, the processing of complement coercion recruited different brain regions than more traditional semantic and syntactic violations (*the novelist astonished/write the book*, respectively), suggesting that coercion processes are a part of the core of the language faculty but do not recruit the wider network of brain regions underlying semantic and syntactic violations. ■

INTRODUCTION

To understand a sentence, comprehenders must deploy both syntactic and semantic knowledge of their grammar. Our understanding of how semantic knowledge is used on-line to compose sentence meanings has been rather limited. However, the past decade has seen an exciting series of studies addressing, arguably for the first time, the processing of sentence-level semantic composition. These studies differ from previous work on semantic processing in that they manipulate the compositionality of sentences, a deep property of language that is invoked to explain how, although speakers have only a finite set of words, they can both produce and comprehend utterances that have never been spoken or heard before (Pelletier, 1994). At present, however, very few studies have explored how the compositional operations that combine sentence meanings together are supported by neural function.

Pylkkänen and McElree (2007) identified two barriers that have impeded research on the neural organization of semantic composition and that the present study seeks to address. The first barrier has been the heavy reliance on violation paradigms to investigate sentence-level semantic processing. Violation paradigms target semantically anom-

alous sentences that subjects judge to be unacceptable. However, the processing of unacceptable sentences may not reflect normal linguistic processes. A number of factors may confound these studies, including those processes that ultimately lead to the rejection of an anomalous sentence (Zhu et al., 2009; Kaan & Swaab, 2002; Indefrey, Hagoort, Herzog, Seitz, & Brown, 2001). Furthermore, it is unclear whether manipulations of semantic plausibility also manipulate the sentence-level operations that compose a sentence's meaning together (Pylkkänen, Oliveri, & Smart, 2009). As such, violation paradigms may tell us little about the core compositional system of language.

The second barrier that Pylkkänen and McElree (2007) identified is the difficulty of separating compositional semantic operations from syntactic operations, as the former are argued to operate largely in tandem with the latter. To manipulate only compositional semantic operations, special constructions are needed, which are argued to separate semantic composition from syntax. One class of constructions that meets these needs rely on coercion operations to construct a part of their meaning (Pylkkänen, 2008; Pylkkänen & McElree, 2006). It has been argued that coercion operations function independently from the syntax, allowing us to manipulate semantic operations while keeping the number of syntactic operations the same. Pylkkänen and McElree (2007) argued that by exploring the processing of coercion operations, we can address both barriers

that currently impede our understanding of the neural organization of semantic composition. First, sentences that employ coercion operations are judged to be acceptable by speakers, allowing a comparison between grammatical sentences and bypassing the difficulty of relying on violation paradigms. Second, coercion operations are argued to be independent from the syntax, allowing for manipulations of semantic composition independently from syntactic factors. The present study extends research on coercion operations to functional MRI and investigates the neural processing of complement coercion (sentences such as *the author began the book*), which allows for the manipulation of semantic composition without recourse to anomaly and where semantic operations are argued to be divorced from syntactic processes.

Complement Coercion

The grammar of complement coercion allows for manipulations of semantic composition because of the selectional properties of verbs and the availability of coercion operations. Verbs semantically select for particular types of complements. In the sentence *the author wrote the book*, the verb *write* selects for an entity, which is denoted by *the book*, and a single compositional operation combines the meanings of *write* and *the book* together to compose the verb phrase *write the book*. Not all verbs select for entity complements, however. In the sentence *the author began writing the book*, the verb *begin* selects for an event complement, which is denoted by *writing the book*, and a single compositional operation applies to compose the verb phrase *begin writing the book*. Typically, the selectional properties of the verb cannot be violated without leading to an unacceptable sentence. However, in English, the verb phrase *begin the book* is acceptable, even though *begin* selects for an event complement, and *the book* denotes an entity. To compose the verb phrase *begin the book*, a second compositional operation is needed (Jackendoff, 1997; Pustejovsky, 1995).¹ This second compositional operation is said to coerce the denotation of *the book* from an entity to an event. Because *the book* denotes an event after the application of the coercion operation, the usual compositional operation can combine *begin* and *the book* together to compose the verb phrase *begin the book*. The application of coercion is not without consequence; an implicit activity is reflexively added to the meaning of these sentences, and the verb phrase *begin the book* comes to mean begin some activity involving the book.

Although it is difficult to rule out the presence of covert syntax in complement coercion (through, for instance, a silent verb), it has been argued that the resolution of the semantic type mismatch between the verb and its complement in complement coercion is nonsyntactic (Pylkkänen, 2008; Pylkkänen & McElree, 2006; Jackendoff, 1997; Pustejovsky, 1995). Given that complement coercion has a nonsyntactic basis, the processing differences associated with these sentences currently provide the best case for

understanding how compositional semantic operations are deployed without the confound of syntactic operations by providing a condition where compositional operations are performed without further syntactic processing.

Several psycholinguistic studies have been conducted that demonstrate that the processing of complement coercion sentences elicits increased processing times compared with control sentences (McElree, Pylkkänen, Pickering, & Traxler, 2006; McElree, Traxler, Pickering, Seely, & Jackendoff, 2001). These studies have argued that the processing cost of complement coercion is related to the deployment of the coercion operation, which constructs the event-denoting meaning of the complement (Traxler, Pickering, & McElree, 2002, but cf. de Almeida & Dwivedi, 2008; de Almeida, 2004, for a pragmatic account of complement coercion and Pickering, McElree, & Traxler, 2005, for evidence against a pragmatic account). These studies have also ruled out a number of alternative hypotheses concerning the source of this processing cost, including contextual effects and competition between alternative interpretations (Frisson & McElree, 2008; Pickering et al., 2005; Traxler, McElree, Williams, & Pickering, 2005).

Initial work on the neurological underpinning of complement coercion has been studied in EEG, magnetoencephalography (MEG), and aphasia, and results have been equivocal. Several different brain regions have been argued to underlie complement coercion, including regions in the left temporal and frontal cortices. Piñango and Zurif (2001) studied the comprehension of complement coercion sentences in Broca's and Wernicke's aphasics. Patients listened to coercion and control sentences in a picture-matching task. Both patient groups performed above chance on coercion and control sentences with only a slight decrement for coercion sentences (Broca's: coercion = 88%, control = 94.6%; Wernicke's: coercion = 74%, control = 92%). This difference reached significance only for the Wernicke's patients. This suggests that the damaged regions of these two Wernicke's patients, overlapping in the left posterior temporal cortex, may have supported a function used in coercion processes, although the high overall performance of these patients also suggests that other factors are involved.

Using MEG, Pylkkänen and McElree (2007) reported that the processing of coercion elicited a frontal component in the 350- to 500-msec time window, which they termed the anterior midline field (AMF). This differed from the processing of semantic violations, which yielded a temporal component in the 300- to 400-msec time window, similar to that found in other studies of word- and sentence-level processing (M350; see Pylkkänen & Marantz, 2003). Interestingly, the AMF component was localized in ventromedial PFC (vmPFC), an area outside the traditional network of brain regions thought to underlie language processing.

The localization of the AMF in vmPFC has led to several intriguing hypotheses on how vmPFC might support semantic processing, but caution concerning localization

of MEG components is warranted. The number of dipoles underlying an MEG component is rarely clear (Green & MacDonald, 2009), and minimizing the number of dipoles in a particular analysis constitutes only “a very weak argument” for the hypothesized neural generators (Nunez & Srinivasan, 2006, p. 80). The localization of the visual M100 is an instructive case, which may be analogous to the AMF. The M100, found in the occipital cortex, is known to be bihemispheric; however, a single midline dipole solution is often found because the source of the left hemisphere dipole and sink of the right hemisphere dipole tend to occur below the sensor array, and the localization algorithms used assume a single source of activity when possible. A similar account can be made for the localization of the AMF. Assuming bihemispheric dipoles for the AMF, the pattern of source and sink suggests that the AMF may have originated from more traditional language areas such as inferior frontal gyrus (IFG). Also, although other sources/sinks could perhaps distinguish between a bihemispheric and midline dipole solution, experimental data are often noisy and unclear. Lau, Almeida, Hines, and Poeppel (2009), for example, provide a clear case for the difficulty of the inverse problem in anterior sensors. In a sentence-level processing experiment, they report three clusters of significant activity during a 350- to 450-msec window: a left anterior source, a right anterior source, and a left posterior source. The relationship between these three sources of activity and their underlying neural generators is uncertain—they could be related to a left lateralized dipole and a midline dipole or to bilateral dipoles with noise masking the right anterior source. Each hypothesized localization has very different consequences for the neural organization of sentence processing and selecting between these two hypotheses or other possible hypotheses will require not only future research using MEG but also converging evidence from other methodologies, including fMRI as the study here seeks to do.

Recent ERP experiments also support a different interpretation of the MEG localization of complement coercion operations. Unlike MEG, which finds distinct neural components for complement coercion and semantic violations, ERP studies report an N400-like component evoking greater amplitude to complement coercion compared with control sentence baselines (Kuperberg, Choi, Cohn, Paczynski, & Jackendoff, 2010; Baggio, Choma, van Lambalgen, & Hagoort, 2009). Unlike the AMF, this N400-like component did not differ topographically from the N400 response to semantically implausible sentences as might be expected if the underlying generators of complement coercion were in vmPFC. These studies instead point toward brain regions that underlie the N400 response, which include IFG (Kuperberg, Sitnikova, & Lakshmanan, 2008; Stringaris, Medford, Giampietro, Brammer, & David, 2007; Cardillo, Aydelott, Matthews, & Devlin, 2004; Kuperberg, Holcomb, Sitnikova, Greve, Dale, & Caplan, 2003; Kiehl, Laurens, & Liddle, 2002; Kang, Constable, Gore, & Avrutin, 1999).

The conflicting results of all these studies point to the need for further research on the neural organization of coercion processes to better understand these differences.

Research Using Semantic Violations

Although the processing of complement coercion has yet to be addressed in fMRI, studies on semantic processing using violation paradigms have made use of this methodology. Although these studies confound sentence acceptability and may elicit activity resulting from a variety of other factors, including attempts at contextual repair and unacceptability judgments resulting from a breakdown at some level or levels of sentence processing (Zhu et al., 2009; Kaan & Swaab, 2002; Indefrey et al., 2001), they provide us with a rich source of hypotheses concerning the brain regions supporting semantic composition. These regions include not only the left IFG but also the left anterior temporal cortex (ATC) and left angular gyrus (AG). A recent review of the literature by Lau, Phillips, and Poeppel (2008) found consistent activation of the left IFG for processing sentences with anomalous endings, which elicit N400s in ERP studies. They concluded that the left IFG facilitates controlled lexical retrieval on the basis of top-down information and selection of lexical candidates, which are stored and accessed in the left middle temporal gyrus (MTG). As such, the left IFG has yet to be shown to perform the kinds of operations needed for semantic composition. The left ATC, however, is thought to underlie sentence-level syntactic processes. Activity in the left ATC is greater when comparing sentence processing to nonmeaningful baselines and lexical level baselines (Crinion, Lambon-Ralph, Warburton, Howard, & Wise, 2003; Bavelier et al., 1997). Comparing neural processing of sentences to word lists or sentences containing meaningless words also shows increased activity in ATC (Humphries, Love, Swinney, & Hickok, 2005; Friederici, Meyer, & von Cramon, 2000). Syntactic priming reduces activation in ATC, reflecting either syntactic or thematic operations (Noppeney & Price, 2004). Finally, selective damage to the left ATC leads to impairments in sentence comprehension (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004). Bilateral AG, although also sensitive to syntactic processes, is thought to support sentence-level semantic processes. Activity increases in the bilateral AG in response to words compared with nonwords and to semantically congruent sentences compared with semantically related word lists or meaningless sentences (Humphries, Binder, Medler, & Liebenthal, 2007), and selective damage to this region impairs performance on complex sentences (Dronkers et al., 2004).

Neural Predictions

In the present study, we manipulated the semantic composition of sentences, following Pykkänen and McElree (2007). On the basis of the fMRI literature on the neural

basis of the N400 and a bilateral dipole localization of the AMF, we predict that coercion processes are localized in IFG. However, we also entertain two alternative hypotheses. First, coercion processes may localize to superior frontal regions, in particular vmPFC, consistent with the single dipole solution of the AMF. Second, coercion processes also may differentially burden the AG and the ATC, areas argued to be involved in basic sentence-level operations and contextual integration.

METHODS

Participants

Twenty-three right-handed, healthy, native English-speaking Michigan State University students naive to the stimuli participated in the study. All volunteers signed a consent form approved by the Michigan State University Institutional Review Board. Data from subjects performing with less than 80% accuracy in the behavioral task were discarded, as they may have not been performing the required task. Four subjects were excluded by this criterion. A total of 19 subjects (7 men and 12 women; mean age = 20.5 years, range = 19–28 years) were included in the analysis.

Materials

The stimuli included 224 sentences that were modified and extended from those in Pylkkänen and McElree (2007). Each sentence was seven words long, consisting of a two-word definite subject (the noun) followed by a verb that was manipulated, a two-word definite object (the noun), and a two-word ending, typically a locative or temporal modifier. Coercion condition sentences used an event selecting verb (*attempted, began, completed, endured, enjoyed, finished, mastered, started,* and

tried). The direct object noun phrases were all entity-denoting, as evidenced by previous work demonstrating that event denoting noun phrases do not elicit a coercion cost in behavioral tasks (Traxler et al., 2002). Control condition verbs were normed by six subjects from Michigan State University using a sentence completion task. Subjects were presented with sentences, such as *The novelist was beginning to _____ the book after breakfast*, and asked to fill in the blank with the first word that came to mind. The most frequent verb that had an orthographically variant past tense form was used as the control verb for the control condition sentences (see Appendix A). The frequency of our coercion and control verbs were not significantly different, although there was a numerical trend for the coercion condition verbs to be more frequent than the control verbs (Birmingham University/COBUILD corpus: coercion = 460; control = 584; $t(221) = 1.703, p = .090$). Violation sentences were constructed to provide a comparison with the literature on sentence-level processing. Semantic violation conditions were constructed using verbs that required animate direct objects. Syntactic violation condition sentences were constructed by removing the tense marker from the verbs. Example stimuli are presented in Table 1.

Paradigm for fMRI

A rapid event-related design paradigm was controlled by a computer equipped with E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA). The visual stimuli were presented on a 1024 × 768, 32-in. LCD monitor with 10° × 13° of visual angle. Sentences were presented one word at a time in Courier New font in the center of the screen. Function words were presented for 200 msec, and content words were presented for 300 msec. A 100-msec delay was

Table 1. Examples of Stimuli for Each Condition

Condition	Sentence
Coercion	The novelist began the book before break.
	The gymnast attempted the beam in competition.
	The toddler enjoyed the cupcake before napping.
Control	The novelist wrote the book before break.
	The gymnast walked the beam in competition.
	The toddler ate the cupcake before napping.
Semantic violation	The novelist annoyed the book before break.
	The gymnast alarmed the beam in competition.
	The toddler comforted the cupcake before napping.
Syntactic violation	The novelist write the book before break.
	The gymnast walk the beam in competition.
	The toddler eat the cupcake before napping.

presented between each word. This allowed for each sentence to be presented in 2500 msec (the time of repetition in image acquisition). After each sentence, participants were instructed to make an acceptability judgment concerning the sentence just presented. Acceptable sentences were indicated by pressing a button with the left index finger, and unacceptable sentences were indicated by pressing a button with the right index finger. A short training session outside the scanner was conducted to familiarize subjects with the acceptability task and the speed of sentence presentation.

The experiment was divided into four functional runs each lasting 7 min, 10 sec. In each run, following a 10-sec baseline condition (a fixation cross), the stimulus trials (14 for each condition, 56 total stimuli per run) and baseline conditions were pseudorandomly arranged using the *RSFgen* program in AFNI software (Cox, 1996) for optimizing the calculation of the hemodynamic response function for each stimulus condition and for the contrasts between them. At least one fixation cross was presented between the stimulus trials to allow subjects time to make an acceptability judgment to the sentence they had just read. The stimuli for all trials and the fixation cross were presented in white on a black background.

Imaging Acquisition

The experiment was conducted on a GE 3T Signa® HDx MR scanner (GE Healthcare, Waukesha, WI) with an eight-channel head coil. During each session, images were first acquired for the purpose of localization, and first and higher-order shimming procedures were then carried out to improve magnetic field homogeneity (Kim, Adalsteinsson, Glover, & Spielman, 2002). To study brain function, EPIs starting from the most inferior regions of the brain were then acquired with the following parameters: 34 contiguous 3-mm axial slices in an interleaved order, time of echo = 27.7 msec, time of repetition = 2500 msec, flip angle = 80°, field of view = 22 cm, matrix size = 64 × 64, ramp sampling, and with the first four data points discarded. Each volume of slices was acquired 168 times during each of the four functional runs while a subject viewed the stimuli and pressed a button to respond, resulting in 672 volumes of images over the course of the entire experiment. After the functional data acquisition, high-resolution volumetric T_1 -weighted spoiled gradient-recalled images with cerebrospinal fluid suppressed were obtained to cover the whole brain with 120 1.5-mm sagittal slices, time of inversion = 500 msec, flip angle = 8°, and field of view = 24 cm.

Behavioral Analysis

Behavioral data were analyzed using repeated measures ANOVA, separately for accuracy and response time, with sentence type as the factor (coercion, control, semantic

violation, syntactic violation), followed by pairwise comparisons correcting for multiple comparisons.

fMRI Data Preprocessing and Analysis

All fMRI data preprocessing and analysis were conducted with AFNI software (Cox, 1996). For each subject, acquisition timing difference was first corrected for different slice locations. With the first functional image as the reference, rigid body motion correction was done in three translational and three rotational directions. The amount of motion in these directions was estimated, and then the estimations were used in data analysis. For each subject, spatial blurring with a FWHM of 4 mm was applied to reduce random noise (Parrish, Gitelman, Labar, & Mesulam, 2000) and also to reduce the issue of intersubject anatomical variation and Talairach transformation variation during group analysis. For the group analysis, all images were converted to Talairach coordinate space (Talairach & Tournoux, 1988) with an interpolation to 1-mm³ voxels. Throughout the article, the coordinates of brain activity are presented in the Talairach space in the format of (RL, AP, IS) with respect to the max t value, wherein R = right, L = left, A = anterior, P = posterior, I = inferior, and S = superior.

For the data analysis of each individual subject, the impulse response function (IRF) was resolved with multiple linear regressions at each voxel with respect to each stimulus condition using the *3dDeconvolve* software in AFNI (Ward, 2000a). The IRFs were resolved to 7 points from 0 to 15 sec at the resolution of 2.5 sec (time of repetition). The 0 point was locked to the middle of the sentence. The BOLD signal change was calculated on the basis of the area under the IRF curve. The equivalent BOLD percent signal change relative to the baseline state was then calculated. General linear tests were applied on a voxel-wise basis to find the statistical significance of pairwise comparisons of the BOLD signal change for the four stimulus conditions. For the above data processing, MRI signal modeling also included the subject motion estimations in the three translational and the three rotational directions and the constant, linear, and quadratic trends for each of the four functional runs.

Whole-brain Analysis

After the percent signal change was estimated with respect to each stimulus condition for each subject, an ANOVA was performed over the 19-subject data set for group analysis with a mixed-effect two-factor model. The stimulus condition (four levels: coercion, control, semantic violation, and syntactic violation) was the first factor and was modeled to provide a fixed effect. Subject was the second factor and was modeled as a random effect. The ANOVA results were used to extract the active voxels for all contrasts.

The ANOVA results were further corrected to estimate the overall statistical significance with respect to the whole brain for multiple comparisons based on Monte Carlo

simulation of the effect of matrix and voxel sizes of the imaging volume, spatial blurring, voxel intensity thresholding, masking and cluster identification using the medium-sized brain from these subjects as the imaging volume (Ward, 2000b). The *active* (significantly different) voxel selection criteria required that the voxels had voxel-based $p \leq .005$ and were nearest-neighbor and within a cluster size of 355 mm^3 . On the basis of application of these criteria to the whole brain, the voxel-based $p \leq .005$ was corrected to be an equivalent whole-brain corrected $p \leq .024$.

ROI Analysis

ROIs were defined in Talairach coordinate space using a combination of functional activation data and previously described anatomical boundaries. Three ROIs in the left Brodmann's area (BA) 45, left MTG, and left inferior parietal lobule (IPL) were functionally defined on the basis of the results of the coercion–control contrast in the whole-brain group analysis (whole-brain corrected $p \leq .024$). Three more ROIs in the left and the right AG and the left ATC were functionally defined on the basis of the results of the grammatical (coercion and control)–ungrammatical (semantic and syntactic violation) contrast in whole-brain group analysis (whole-brain corrected $p \leq .024$).

In addition to these functionally defined ROIs, we constructed an ROI homologue for the right BA 45 by reflecting the coordinates from the left hemisphere for these regions onto the right hemisphere. We also constructed two spherical ROIs centered at (R4, A49, S36) and (L4, A49, S36), each with a radius of 4, representing the left and the right vmPFC to further test hypothesized contrasts. These areas closely corresponded to the dipole localization of the AMF that was found to be active to complement coercion in MEG (Pylkkänen & McElree, 2007).

Although some of these ROIs are functionally defined by the activity of our conditions, we were interested in the pattern of activation across our four conditions within each of these ROIs. The mean BOLD percent signal change at each stimulus condition at each ROI was extracted from each subject. These mean BOLD percent signal changes were entered into Statistical Package for the Social Sciences for Windows (Version 14.0; SPSS Inc., Chicago, IL) and analyzed using repeated measures ANOVA with sentence type as the factor (four levels: coercion, control, semantic violation, syntactic violation), followed

by pairwise comparisons with correction for multiple comparisons.

RESULTS

Behavioral Results

Accuracy and response time data are given in Table 2. Subjects were able to correctly reject sentences with violations while accepting correct sentences. A repeated measures ANOVA found a significant effect of Sentence Type on Accuracy [$F(3, 16) = 6.145, p = .001$]. Coercion sentences were less accurate overall than other conditions [vs. control: $t(18) = 3.281, p < .005$; vs. semantic violation: $t(18) = 3.906, p = .001$; vs. syntactic violation: $t(18) = 3.476, p < .005$]. Although RT latencies were slowest for the coercion condition, a repeated measures ANOVA found no significant effect of Sentence Type on Response Time ($F(3, 16) = 1.509, p = .223$).

Imaging Results

Figures 1 and 2 illustrate the two maps showing significant brain activation for the coercion–control and grammatical–ungrammatical contrasts, respectively. The coercion–control contrast showed differential activity in the left IFG in BA 45 and also in the left MTG, IPL, and SPL (Figure 1 and Table 3). The grammatical–ungrammatical comparison showed differential activity in the left AG, ATC, IPL, MFG, SFG, and MTG bilaterally (Figure 3 and Table 4).

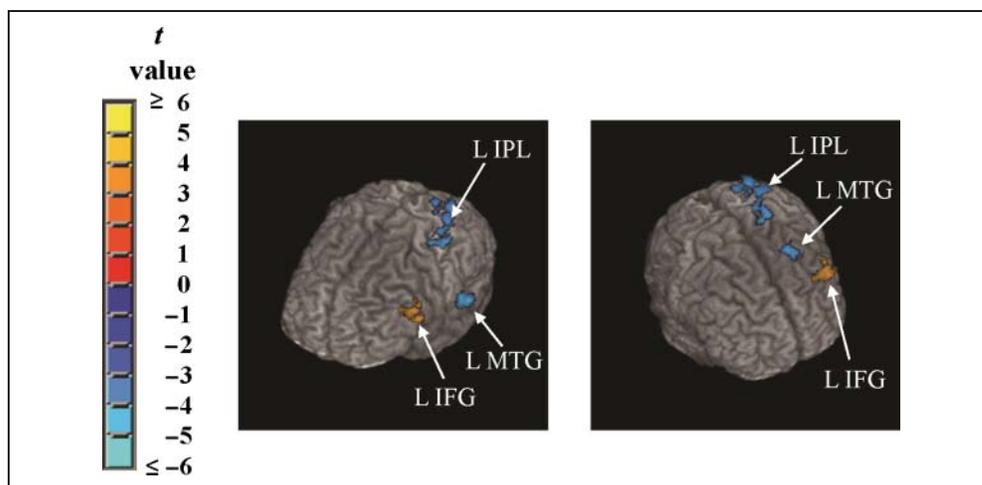
Our main ROI comparisons are given in Figure 3 and Table 5. The left BA 45 showed greater activity for both coercion and semantic violation conditions compared with the control condition. This initially suggests that coercion and semantic violation conditions pattern together; however, from the grammatical–ungrammatical contrast in the whole-brain analysis, these two conditions are distinguished by activity differences in the left ATC and the bilateral AG. Pair-wise comparisons sharpen this observation, showing that the syntactic violation condition primarily drives the effect in the left ATC whereas the semantic violation condition drives the effect for the right AG. The left AG shows a clear distinction between grammatical and ungrammatical sentences. The left ATC and the bilateral AG are generally thought to underlie sentence-level processes but in this study, they do not distinguish between coercion and control sentences that differ in the number of sentence-level compositional operations they require. Only the left

Table 2. Subjects' Mean Response Accuracy and RT by Sentence Condition

	<i>Coercion</i>	<i>Control</i>	<i>Semantic Violation</i>	<i>Syntactic Violation</i>
Accuracy (%)	79.8 (2.0)	88.7 (1.3)	90.4 (2.6)	89.2 (1.8)
RT (msec)	830 (40)	802 (41)	812 (48)	778 (43)

Standard error is given in parentheses.

Figure 1. The spatial extents of differential activation for the coercion–control contrast in the whole-brain analysis (voxel-wise t value scale on the left) shown through color maps (voxel base $p \leq .005$ and whole-brain corrected $p \leq .024$). Key active regions are indicated. R = right, L = left.



IFG makes this distinction with the coercion condition eliciting greater activity in the left IFG compared with the control condition. Additional differences in our whole-brain analysis show overall decreases in activity for the coercion condition compared with the control condition in the left MTG and IPL. Pair-wise comparisons found that both violation sentences also elicited decreased activity compared with the control condition in the left MTG and IPL. Although this again suggests that the coerce condition is similar to the violation conditions, we will offer an alternative explanation below.

DISCUSSION

Much of what we currently know about sentence-level semantic processing comes from studies that have manipulated semantic congruency and expectancy. These studies have served to delimit hypotheses about the underlying neural regions that support semantic composition, but possible confounds in comparing nonsense sentences to grammatical sentences have limited their usefulness, and it is not clear if manipulations of semantic plausibility target the sentence-level semantic operations, which compose a

sentence's meaning. In this study, we used complement coercion to manipulate the semantic composition of sentences without changing their syntax or plausibility. The processing of complement coercion sentences elicited greater activation in BA 45 in the left IFG.² This finding contrasted with the activation patterns elicited by sentences containing semantic and syntactic violations. In particular, although both coercion and semantic violation conditions elicited greater left IFG activation, semantic violations recruited a much wider network of brain regions. This suggests that cases of complement coercion are distinguished from semantic violations by the networks of brain regions that support their respective processing.

Complement Coercion and Left IFG

Previous behavioral literature has argued that the processing cost of complement coercion is based on the application of coercion processes that construct the event-denoting meaning of the complement. Consistent with this, we propose that the left IFG supports the application of coercion processes. We also propose that the left IFG supports the detection of a semantic type mismatch between the verb

Figure 2. The spatial extents of differential activation for the grammatical–ungrammatical contrast in the whole-brain analysis (voxel-wise t value scale on the left) shown through color maps (voxel base $p \leq .005$ and whole-brain corrected $p \leq .024$). Key active regions are indicated. R = right, L = left.

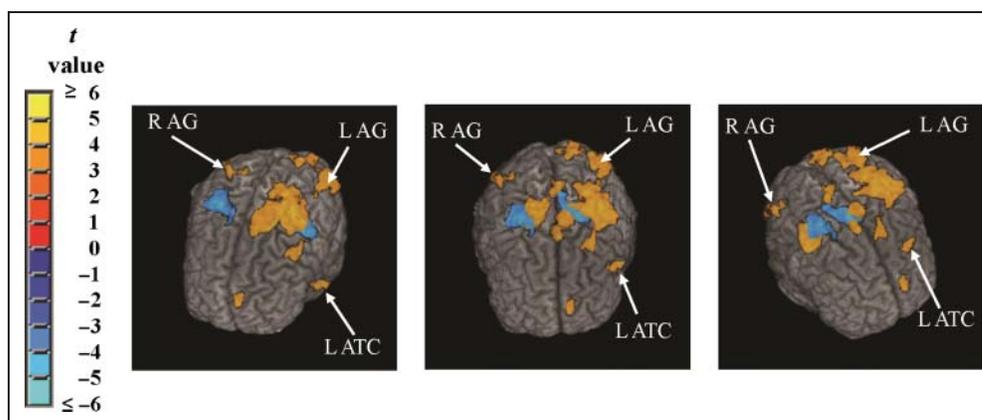


Table 3. The Differentially Active Regions of the Coercion–Control Contrast from Whole-brain Group Analysis

Location	L/R	Volume (mm ³)	Mean <i>t</i> Value	Max <i>t</i> Coordinate	Mean Signal Change (%)	
					Coerce	Control
BA 45	L	113	3.62	(150, A22, S10)	1.14	0.78
IFG	L	364	3.55	(150, A22, S10)	1.10	0.79
IPL	L	325	−3.53	(L37, P40, S56)	0.08	0.37
MTG	L	226	−3.85	(L51, P35, I9)	0.21	0.42
SPL	L	256	−3.59	(L30, P53, S59)	−0.15	0.16

and its complement, consistent with the literature on left IFG. Both of these processes are important: If the left IFG only detected the semantic type mismatch, it would leave cases of complement coercion without repair (Traxler et al., 2005); however, if the type mismatch went undetected, the coercion operation would never be triggered. We discuss both of these operations in turn.

To deploy a coercion operation, the system must first recognize that a semantic type mismatch has occurred between the verb and its complement. Certain cases of error detection driven by mismatch in language processing are known to affect activity in the left IFG. One area of research that finds activation of the left IFG in response to a mismatch is subject–verb agreement violations (Newman, Just, Keller, Roth, & Carpenter, 2003; Indefrey et al., 2001; Moro et al., 2001; Ni et al., 2000). In English, subjects and their verbs must agree in number marking, and sentences in which a subject and its verb disagree in number are judged to be unacceptable. In violation paradigms that compare subject–verb agree-

ment violations to grammatical controls, activity in the left IFG is generally found to increase. A second area of research that finds activation of the left IFG to mismatch is verb animacy violations (Kuperberg et al., 2008; Chen, West, Waters, & Caplan, 2006). As with complement coercion, certain verbs require that their arguments be animated. To detect the unacceptability of these sentences, the selectional properties of the verb must be checked against the properties of its arguments. In violation paradigms that compare sentences that have a mismatch between verb animacy requirements and the animacy of its arguments, activity in the left IFG is found to increase. In the present study, which employed verb animacy violations for its semantic violation, increased activity in the left IFG was also found. The shared mechanism between complement coercion, subject–verb agreement violations, and verb animacy violations is the detection of a mismatch. Our proposal that the left IFG acts as a detector for these types of local mismatches in language processing provides a single unified account of these studies. Importantly,

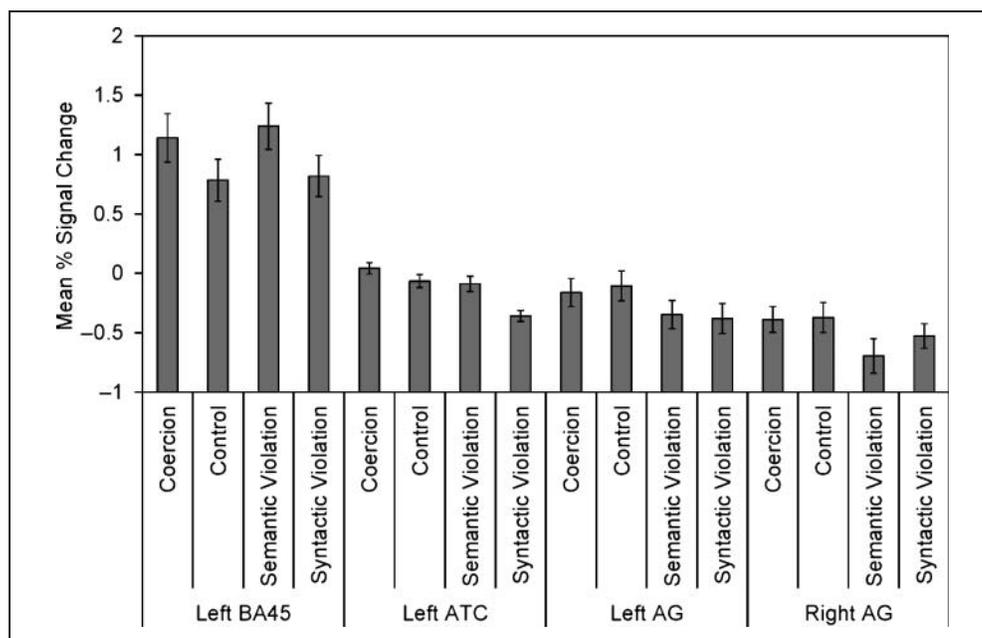
Figure 3. Mean percent signal change by condition and ROI for the coercion, control, semantic violation and syntactic violation conditions. The error bars represent *SEMs*.

Table 4. The Differentially Active Regions of the Grammatical–Ungrammatical Contrast from Whole-brain Group Analysis

Location	L/R	Volume (mm ³)	Mean <i>t</i> Value	Max <i>t</i> Coordinate	Mean Signal Change (%)	
					Grammatical	Ungrammatical
AG	L	554	3.85	(L45, P65, S30)	−0.14	−0.37
ATC	L	431	3.91	(L46, A1, I27)	−0.01	−0.22
IPL	L	628	3.76	(L29, P39, S57)	0.22	−0.07
MFG	L	450	3.83	(L6, P15, S50)	0.27	0.15
MTG	L	1418	3.73	(L45, P65, S29)	0.07	−0.17
SFG	L	427	3.59	(L6, A58, S23)	−0.06	−0.53
AG	R	146	3.56	(R45, P65, S32)	−0.38	−0.62
MTG	R	337	3.56	(R45, P65, S28)	−0.19	−0.39

however, unlike subject–verb agreement and verb animacy violations that lead to unacceptable sentences, the detection of the mismatch in complement coercion is clearly local to the compositional semantic system and triggers a compositional operation that quickly resolves the mismatch. Therefore, unlike semantic (i.e., world knowledge) violations, the mismatch and its repair only affect semantic composition and do not recruit other processes for repair or rejection. This may also be reflected in the more constrained cortical network found for complement coercion in this study than is typically found using violation paradigms where arguably multiple processes break down.

Once a semantic type mismatch is detected, the system must check to see if there is a repair operation available and, if available, deploy that operation. In the case of complement coercion, a repair is available, namely, coercing the semantic type of the noun denotation from an entity to an event. This shift from an entity to an event also draws on operations supported by the left IFG. There are two alternatives to consider. Assuming event meanings for nouns are also stored in the lexicon (Pustejovsky, 1995), IFG may function to select and retrieve the noun's event-related meaning. This selection and retrieval process could invoke the same mechanisms as those used

Table 5. Summary of ANOVA and Pair-wise Comparisons for Each ROI

	<i>F</i>	Coercion			Control		Semantic Violation
		Control	Semantic Violation	Syntactic Violation	Semantic Violation	Syntactic Violation	Syntactic Violation
<i>Left Hemisphere</i>							
BA 45	11.950***	2.330*		2.102*	−2.963**	−2.102*	2.741*
MTG	11.135***	−4.289***			3.314**	4.055***	
IPL	11.844***	−3.509**			4.520***	4.276***	
ATC	34.742***		2.187*	6.702***		4.899***	4.515***
AG	11.227***		2.641*	3.131***	3.411**	3.902***	
vmPFC	5.234**			1.789**			
<i>Right Hemisphere</i>							
AG	5.754**		3.381**		3.558**		
BA 45							
vmPFC							

p* < .05.*p* < .01.****p* < .001.

in typical cases of lexical access (Lau et al., 2008). The retrieval task of the left IFG is also supported by the N400 found in electrophysiological studies of complement coercion under the theory that the N400 is an index of the difficulty of lexical retrieval (Kuperberg et al., 2010; Baggio et al., 2009). If the event-denoting meaning of a noun is less active, then the difficulty in accessing it may be reflected by this component. One problem faced by this account is the lack of evidence for a cost in complement coercion sentences associated with the selection of a particular meaning (Frisson & McElree, 2008). However, although no cost has been detected for the competition and selection of a particular meaning, the meaning of the implicit activity in complement coercion sentences might not remain ambiguous. Certainly, it is possible that, although a cost associated with the competition and selection of a particular meaning is not detected in eye movement studies, the cost is reflected by differential neural activity. The alternative account, consistent with Frisson and McElree (2008), is for the left IFG to support the deployment of the coercion operation itself by applying the coercion operation to the unfolding semantic representation of the sentence—a claim currently favored in the literature. Application of a coercion operation may draw on general combinatoric operations supported by the left IFG such as unification (Hagoort, 2005) or type shifting (Pylkkänen & McElree, 2006). The combinatoric operation of the left IFG is also supported by the N400 found in electrophysiological studies of complement coercion under the theory that the N400 is an index of the difficulty of semantic integration (Kuperberg et al., 2010; Baggio et al., 2009). It is important to note that the other cases of mismatch above do not have access to a repair mechanism like coercion. Subject–verb agreement violations cannot be repaired and are rejected by speakers. Animacy violations do not fair much better. To resolve animacy violations, world knowledge must be violated by allowing an animate interpretation of the inanimate noun. Only rich fantasy contexts can easily allow these interpretations. For animacy violations, other neural systems are brought into play, which may act to resolve the implausibility of the sentence meaning with the current context. This process may be mediated by other brain regions including the bilateral AG.

An alternative interpretation of increased activity in the left IFG worth considering is that the verbs that allow for complement coercion are ambiguous between two subcategorization frames. Verbs like *begin* may either take a verb phrase complement as in *begin writing the book* or a noun phrase complement as in *begin the book*. Although a number of subcategorization frames is not found to affect behavioral or eye movement measures (Schmader, Kennison, & Clifton, 1991; Shapiro, Zurif, & Grimshaw, 1987), fMRI studies find activity differences for subcategorization in the left IFG (Shetreet, Palti, Friedmann, & Hadar, 2007), making it initially plausible for the left IFG activity to be related to the difference in the number of subcategorization frames between coercion verbs and control verbs.

However, Shetreet et al.'s study found that verb subcategorization frames increased activity in BA 9 and BA 47, whereas the present study found increased activity in BA 45. Also, studies of complement coercion find processing differences occurring on the head noun of the complement and not on the verb or determiner (Kuperberg et al., 2010; Baggio et al., 2009; Pylkkänen & McElree, 2007; Traxler et al., 2002; McElree et al., 2001), and when the noun denotes an event, no processing cost is found (i.e., *fight* vs. *puzzle*, Traxler et al., 2002). Together, these studies argue against a subcategorization frame account of complement coercion costs, although further research may be needed to specifically address the role verbs themselves have on the processing of complement coercion.

We also found several areas of the brain where the processing of complement coercion appears to be less active than the processing of control sentences, but these effects appear to be due to priming and repetition. The decrease in the left MTG and IPL activity may be because of priming of our event-selecting verbs compared with our control condition verbs. The number of verbs that participate in complement coercion are small and appeared frequently in our study. This frequency effect may have led to repetition suppression or decreases in activation (Gagnepain et al., 2008). We conclude that this deactivation is not related to the processing of complement coercion. Importantly, although the coercion condition verbs were repeated more times than the control condition verbs, we still found a robust increase in activity in the left IFG. This further supports the interpretation that this activity is not linked directly to the presentation of the verbs themselves but, instead, is the result of initiating complex compositional operations required to compute the meaning of complement coercion sentences.

Overall, this study argues that the left IFG subserves the processing of complement coercion by detecting a semantic type mismatch between an event-selecting verb and an entity-denoting noun and applying a coercion operation to the unfolding semantic representation of the sentence.

ATC, AG, and Nonlocal Errors

Other brain regions that have been argued to support sentence-level processes like the left ATC and the bilateral AG were not found to be differentially affected by the semantic composition manipulation in this study. Instead, these regions were found to be differentially affected by grammaticality. In general, greater activity was elicited by coercion and control sentences than semantic and syntactic violation sentences. Because the left ATC and the bilateral AG were not sensitive to the difference in semantic composition between coercion and control, we suggest that these two regions may not actually reflect differences in *grammatical* sentence-level semantic processing. Instead, these two regions may be sensitive to errors in sentence processing. Although this study was not designed to specifically address the nature of errors

in sentence processing, the following interpretation would be consistent with our results. Decreased activity in these regions in the face of an error in sentence processing may be the result of a halt in normal processing. For example, syntactic agreement errors may act to halt the normal syntactic parse of the incoming sentence in the left ATC. A reduction in activity in this region would be expected because left ATC supports normal syntactic parsing (Humphries, Binder, Medler, & Liebenthal, 2006). Similar reasoning may apply to AG. The AG is thought to support sentence-level semantic processing (Humphries et al., 2007). Assuming that sentence meanings function to update the discourse context (Chierchia, 1994), we may reinterpret this region as supporting the updating of discourse context. Syntactic errors or semantic violations, such as those resulting from animacy violations, may prevent the sentence meaning from updating the discourse context. Taking the bilateral AG as the neural regions supporting discourse context, a reduction in these regions in response to these errors would be expected. Because coercion and control condition sentences in this study engender no sentence-processing errors, we do not expect these regions to distinguish between them. The number of syntactic operations is the same between these two conditions, and both form sentence meanings capable of being added to a normal discourse context. Although this interpretation of the activity of the left ATC and the bilateral AG is tentative, it highlights the importance of studies that manipulate semantic composition without involving violation paradigms.

Hemodynamic and Electrophysiological/Neuromagnetic Comparisons

As the first study to monitor the hemodynamic response to the processing of complement coercion sentences, our results concerning the neural substrates underlying coercion processes provide important comparisons to recent electrophysiological and neuromagnetic results. Importantly, different methodologies often yield different and sometimes conflicting results, and these conflicts continue to be debated in the literature (Van Petten & Luka, 2006). We consider the relationship of the results of this fMRI study to those of previous studies on complement coercion using ERP and MEG subsequently.

Our results are comparable with recent ERP studies that find an N400-like response to complement coercion (Kuperberg et al., 2010; Baggio et al., 2009). Although the timing of this N400-like response suggests that processing complement coercion is different from the processing of semantic violations, the topographic similarity between the response to complement coercion and the classic N400 suggests that there is overlap between the neural regions supporting complement coercion and semantic violations. Although no strong claim has been made concerning the underlying neural generators of this N400-like response to complement coercion, our

results implicate left IFG as an important region, consistent with research finding the left IFG in response to classic N400 paradigms (Kuperberg et al., 2003, 2008; Stringaris et al., 2007; Cardillo et al., 2004; Kiehl et al., 2002; Kang et al., 1999).

Our results are not consistent, however, with similar studies using MEG, especially concerning the localization of the coercion effect. We are unable to support the vmPFC localization of the AMF because we failed to find differential activity in this region sensitive to coercion. Indeed, the vmPFC localization of the AMF has received little independent evidence outside MEG methodologies. Brennan et al. (2010), for instance, do not report activity in vmPFC during a story-listening task using fMRI, although Brennan and Pylkkänen (submitted) do report activity in vmPFC during a story-listening task using MEG. Ultimately, it is possible that MEG is sensitive to the activity in vmPFC that goes undetected in fMRI, although a signal-to-noise ratio analysis of vmPFC indicated that our study was capable of imaging differences in this region (temporal signal to noise ratio = 70.5; Parrish et al., 2000). Importantly, our results do not bear on the timing of the AMF, which we take to demonstrate a clear neuromagnetic distinction between complement coercion and semantic violation. That said, further research is needed to confirm the results of each of these studies and bring broader consensus to the cortical network underlying semantic composition.

Conclusion

In this study, we manipulated the compositionality of sentences to examine the neural correlates of sentence-level semantic processing. Our results show that complex compositional operations like coercion elicit greater activity in the left IFG. The brain regions that subserve the processing of complement coercion are different from those recruited for the processing of sentences involving semantic and syntactic violations, which resulted in a differential activity of a broader network of brain regions, including the left ATC and the bilateral AG. This result suggests that regions like the left ATC and the bilateral AG are sensitive to grammaticality and plausibility, but not to compositionality, and raises the possibility that these regions are not actually responsible for sentence-level semantic processes.

APPENDIX A

Verbs for control condition are as follows: ate, attended, bought, built, carved, chased, chewed, chopped, cleaned, climbed, colored, cooked, counted, did, drank, drew, drove, dug, edited, filled, fixed, flew, frosted, gave, heard, honked, jumped, killed, learned, left, made, mixed, mowed, opened, painted, payed, pitched, played, ran, received, revved, rode, sang, saw, searched, sewed, sharpened, shot, smoked, solved, steered, sucked, took, turned, used, walked, watched, wore, wrote.

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