

Cognitive control and parsing: Reexamining the role of Broca's area in sentence comprehension

JARED M. NOVICK, JOHN C. TRUESWELL, and SHARON L. THOMPSON-SCHILL
University of Pennsylvania, Philadelphia, Pennsylvania

A century of investigation into the role of the human frontal lobes in complex cognition, including language processing, has revealed several interesting but apparently contradictory findings. In particular, the results of numerous studies suggest that left inferior frontal gyrus (LIFG), which includes Broca's area, plays a direct role in sentence-level syntactic processing. In contrast, other brain-imaging and neuropsychological data indicate that LIFG is crucial for cognitive control—specifically, for overriding highly regularized, automatic processes, even when a task involves syntactically undemanding material (e.g., single words, a list of letters). We provide a unifying account of these findings, which emphasizes the importance of general cognitive control mechanisms for the syntactic processing of sentences. On the basis of a review of the neurocognitive and sentence-processing literatures, we defend the following three hypotheses: (1) LIFG is part of a network of frontal lobe subsystems that are generally responsible for the detection and resolution of incompatible stimulus representations; (2) the role of LIFG in sentence comprehension is to implement reanalysis in the face of misinterpretation; and (3) individual differences in cognitive control abilities in nonsyntactic tasks predict correlated variation in sentence-processing abilities pertaining to the recovery from misinterpretation.

In 1861, Paul Broca presented the idea that an anterior region within the brain's left hemisphere, the inferior frontal gyrus (IFG), played a special role in language use. Ever since, attempts have been made to characterize more precisely the nature of this relation. One recurring theme within the neurolinguistic literature has been to postulate a direct connection between Broca's area and sentence-level syntactic processing. In favor of this claim, it is often noted that Broca's aphasics show substantial deficits in sentence production but only mild impairments in comprehension, limited mainly to syntactically complex and/or demanding sentences (e.g., Caplan, Alpert, Waters, & Olivieri, 2000; Grodzinsky, 2000; Zurif, Caramazza, & Myerson, 1972). Such a production-comprehension asymmetry could arise because sentence production requires the use of syntactic knowledge for even the simplest of utterances, whereas comprehension may need to tap detailed syntactic knowledge for only structurally complex ones; other cues and nonsyntactic strategies could in principle be employed to understand less complicated sentences. Similarly, brain-imaging studies of healthy individuals reveal activation in Broca's area under conditions of either producing language (e.g.,

Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004) or comprehending language that is syntactically complex and/or ambiguous (e.g., Fiebach, Vos, & Friederici, 2004; Mason, Just, Keller, & Carpenter, 2003). Taken together, these results have been used to support the hypothesis that Broca's area subserves syntactic working memory (WM) or may even be the neural seat of syntactic representations.

There is, however, mounting evidence that this account is incorrect. Metalesion site analyses of aphasics indicate that damage to the posterior region of left IFG (henceforth, LIFG), also known as Broca's area, does not predict specific deficits in grammatical processing for either production or comprehension (Dick et al., 2001; Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004). That is, patients with LIFG damage are not necessarily Broca's aphasics. In fact, all documented cases of patients with restricted lesions to LIFG reveal quite minimal and transient language disorders, showing only occasional confusion in speaking and/or listening (Dronkers et al., 2004; Hamilton & Martin, 2005; Robinson, Blair, & Ciolotti, 1998; Thompson-Schill et al., 2002). These patients' most striking impairments instead involve their inability to override habitual or prepotent response behaviors in goal-directed tasks—for example, Stroop tasks and item recognition tasks that give rise to representational interference. As we discuss in detail below, all of these tasks involve linguistic material but of surprisingly undemanding sorts (e.g., single words, lists of four letters)—certainly not material that requires sophisticated syntactic machinery.¹ Correspondingly, functional neuroimaging studies of healthy adults who are engaged in these same tasks show reliable activation of LIFG under the same conditions of interference (see, e.g., Jonides,

This research was part of J.M.N.'s dissertation work and was supported by NIH Grants R01-HD37507 awarded to J.C.T. and R01-MH67008 awarded to S.L.T.-S. We thank David January and Matthew Botvinick for valuable advice and discussion, and three anonymous reviewers for helpful comments on earlier drafts of the manuscript. Correspondence should be addressed to J. M. Novick, Department of Brain & Cognitive Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139 (e-mail: jnovick@mit.edu).

Smith, Marshuetz, Koeppel, & Reuter-Lorenz, 1998; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). As a whole, these findings suggest that LIFG may play a more general role in cognitive operations and may have little to do with syntactic knowledge or syntactic processing per se. Such hypotheses of LIFG function are appealing in their ability to parsimoniously connect to other putative functions of prefrontal cortex (PFC); however, to date, they have provided no straightforward account of the many neuroimaging findings that indicate LIFG involvement in supporting the syntactic processing of sentences, particularly when the structures are complex or ambiguous (e.g., Fiebach et al., 2004; Mason et al., 2003).

In this article, we attempt to link syntactic and non-syntactic hypotheses of LIFG functioning and thereby to reconcile these apparently contradictory findings by describing the important role of LIFG-mediated cognitive control processes in language comprehension. We argue that this region does not represent, nor even temporarily maintain, syntactic information. Instead, we suggest that LIFG is involved in implementing the control processes necessary to resolve conflicts that arise among the distinct representational subsystems necessary for language use (i.e., phonological, syntactic, and semantic subsystems, each of which reside in other neural regions). Our account relies heavily upon the cognitive control literature, which asserts that under conditions of representational interference or conflict, neural circuitry within PFC, including LIFG, is engaged to bias activation patterns associated with competing representations (and thereby implement reanalysis) in order to prevent and/or correct errors (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miller & Cohen, 2001). We expand upon this account by connecting it to current psycholinguistic theorizing on sentence comprehension and garden-path recovery (i.e., recovery from temporary misinterpretation), focusing especially on those theories that postulate a central role for the coordination of multiple sources of information when recovering a structural characterization of linguistic input (e.g., M. C. MacDonald, Pearlmuter, & Seidenberg, 1994; Trueswell & Tanenhaus, 1994, *inter alia*). The end result, we hope, is a more detailed account of the neural underpinnings of both language comprehension and cognitive control.

Our predictions, which we briefly state here and defend throughout the course of the article, are derived from our view of sentence processing, which is as follows: During sentence comprehension, the recognition of individual words automatically triggers the activation of highly detailed linguistic information, including syntactic and semantic information. That is, as a sentence is processed in real time, partially independent phonological, syntactic, and semantic characterizations are developed in parallel with word recognition processes triggering specification of these representations. These computations are largely driven by probabilistic mechanisms that track the linguistic environments in which words appear. Other sources of information, such as a sentence's refer-

ential context, simultaneously exert an influence. In many cases, all of these evidential sources conspire toward a correct linguistic characterization of the input. However, on rare occasions this evidence will point toward an analysis that ultimately turns out to be incorrect, requiring the system to find an alternative solution. These situations are commonly described as "garden paths," or temporary misinterpretations.

Specifically, we will defend the following three hypotheses, around which the remainder of this article is organized. (1) LIFG is part of a network of frontal lobe subsystems that are generally responsible for the detection and resolution of incompatible stimulus representations. We defend this claim in the section on the Role of LIFG in Conflict Resolution; in particular, we review both neuroimaging and patient evidence from studies exploring the role of PFC in conflict resolution during non-parsing tasks. The evidence suggests that LIFG is part of a neural circuit designed to modulate among mutually exclusive characterizations of perceptual input that independently point toward different responses. (2) The role of LIFG in sentence comprehension is to implement reanalysis in the face of misinterpretation. In the Role of LIFG in Sentence Processing section, we defend this claim by providing a neurofunctional account of sentence processing in which multiple characterizations of the linguistic input are instantiated in partially independent subsystems within the left hemisphere. LIFG's role is not to represent syntactic information, but rather to "push" these representational subsystems to reorganize into another stable state when an incompatibility has been detected. Both patient and neuroimaging evidence will be reviewed.² (3) Within the normal population, individual differences in conflict resolution abilities in nonsyntactic tasks ought to predict similar variation in sentence-processing abilities pertaining to the recovery from misinterpretation. In the section on Individual Differences in Cognitive Control and Language Abilities, we explore and defend this hypothesis. Most research on individual differences in sentence processing has, to date, focused on WM capacity. It follows from our account, however, that individual variation in cognitive control abilities (including how these abilities change over the course of development) should also be good predictors of sentence processing and, in particular, garden-path recovery.

First, however, we must reiterate that although this article is about the function of LIFG and Broca's area, it is *not* about Broca's aphasia. As stated earlier, focal lesions to Broca's area do not yield the array of linguistic deficits collectively referred to as Broca's aphasia. Thus, in our review of the lesion-deficit analyses of Broca's area, we have intentionally omitted discussion of impairments that are observed in patients with Broca's aphasia but whose deficits have not been linked to damage to Broca's area.³ Instead, we make predictions that more aptly consider how Broca's area plays a role in *controlling* linguistic behavior and the implications thereof when the

region is damaged, underdeveloped, or even more or less active in some healthy individuals than in others.

Role of LIFG in Conflict Resolution

As stated above, it is our contention that LIFG, and Broca's area within LIFG, is part of a broad network of frontal lobe systems responsible for the detection and resolution of incompatible representations. This hypothesis is derived from two sets of complementary findings within the neuropsychological and brain-imaging literatures, both of which explore the neural underpinnings of conflict resolution during goal-directed behavior (e.g., Hamilton & Martin, 2005; Jonides et al., 1998; Milham et al., 2001; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003; Thompson-Schill et al., 2002). These studies suggest a functional role for LIFG—namely, that it supports the engagement of the control mechanisms necessary for resolving conflict. As we discuss below, these and related studies indicate that left PFC is involved generally in this process but that LIFG in particular may support the resolution of incompatible linguistic characterizations, which need not be syntactic in nature.⁴

Within this literature, the term *conflict* refers to cases in which an individual receives incompatible information either about how best to characterize a stimulus or how best to respond to that stimulus. Conflict can be induced experimentally by designing situations in which the input automatically triggers an internal representation that is incompatible with the situation-specific demands. The prototypical example of this sort of conflict is the Stroop task (Stroop, 1935), in which participants must name the ink color of printed color terms instead of reading the term itself. For incongruent trials, the stimuli are designed such that word recognition processes give rise to a linguistic representation that conflicts with the task-specific demand of naming the word's ink color (e.g., naming the ink color of the word *blue* when it is colored red). Processing difficulty (e.g., increased response time [RT]) arises on incongruent trials presumably because participants must shift their attention toward task-relevant stimulus characteristics in order to override automatically generated but currently irrelevant representations (e.g., MacLeod, 1991). The process of shifting attention in this and related cases is often termed *cognitive control*, in part because the attention shift does not occur at the sensory level but at some hypothesized internal level of representation. It is important to note that conflict and the engagement of control have also been studied in a range of other related tasks, most notably, for our purposes, an adapted version of an item recognition task (e.g., McElree & Doshier, 1989; Monsell, 1978). Here, participants must decide whether a probe letter (e.g., "K") was part of an immediately preceding set of four letters (e.g., "m k d i"). For most trials in this task, rapid and accurate responses can be accomplished simply by relying on a metric of familiarity—

that is, facilitated recognition of the probe letter due to its recency and/or repetition. Conflict can be induced on a subset of trials by presenting a recognition probe (e.g., "A") that is not a member of the current memory set (e.g., "t b e f") but was a member of the memory set on the *previous* trial (e.g., "a m g p"). Processing difficulty arises on these so-called recent-no trials because participants must battle against the generally reliable (but currently irrelevant) familiarity-based information and instead attend to the foremost activation of the letters from the current set. Thus, incongruent trials in this task and the Stroop task have in common the need to engage control mechanisms that are necessary to resolve conflict.

There is now considerable evidence that left PFC, and LIFG specifically, is responsible for the resolution of conflict in which an internal representation gives rise to a highly regularized but currently irrelevant process. Some of the most compelling evidence comes from two separate case studies of patients with restricted damage to this region (Hamilton & Martin, 2005; Thompson-Schill et al., 2002). These patients, M.L. and R.C., presented with very minor and transient language impairments, substantiating thorough meta-lesion-site analyses of similar patients (for a review, see Dronkers et al., 2004). Critically, however, they demonstrated deficits on incongruent trials in the two tasks described above. For instance, each study independently used the adapted letter recognition task, and both patients showed abnormally high interference effects on recent-no trials for both response latency and accuracy but, notably, performed within the normal range for all nonconflict trials. Figure 1 illustrates R.C.'s performance contrasted with healthy age-matched controls and other left PFC patients whose damage *spared* LIFG (adapted from Thompson-Schill et al., 2002). The data clearly illustrate how a lesion to LIFG selectively impairs the ability to suppress highly reliable but currently irrelevant information (i.e., familiarity information) while performing goal-directed behavior.

Moreover, Hamilton and Martin (2005) tested whether their patient's deficit on this same task generalized to all types of conflict resolution, or whether it was restricted to only those with linguistic stimuli. In particular, M.L.'s performance was also examined on the Stroop task and two nonlinguistic tasks requiring prepotent *motor* responses to be overridden (e.g., on a nonverbal Stroop task and the antisaccade task). Across all tasks, M.L.'s performance revealed that he was impaired on both language-related tasks (Stroop and recent-no trials on the adapted letter recognition task) but crucially not on the tasks that required him to suppress prepotent or automatic motor-response preparations (antisaccade and nonverbal Stroop). In addition, we have recently identified a third patient with a focal lesion to LIFG (Novick, January, Trueswell, & Thompson-Schill, 2004). This patient, N.J., also showed specific impairment on the interference trials of the item recognition task. Moreover,

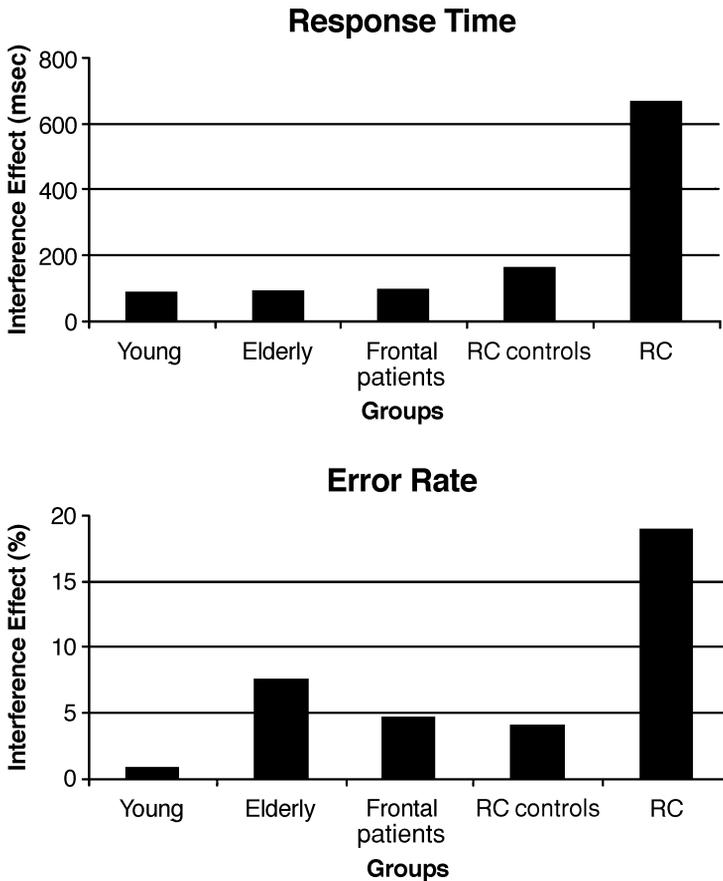


Figure 1. Interference effects on the modified item recognition task (recent-no trials – nonrecent-no trials). This shows the magnitude of interference effects for response time and error rate. R.C., the patient with a restricted lesion to LIFG, demonstrated increased interference effects under conditions of conflict relative to the control groups (data adapted from Thompson-Schill et al., 2002).

N.J. has only minimal language impairments, very similar to these other 2 patients. As a whole, the findings from these 3 patients, R.C., M.L., and N.J., suggest a fundamental role for LIFG in suppressing regularized processes, but only when the conflict was brought about by incompatible representational solutions of the input.

A large number of brain-imaging studies using these same tasks also support this interpretation. In particular, patterns of activity within posterior regions of left inferior PFC, including LIFG, are routinely observed for incongruent trials during the Stroop task (e.g., A. W. MacDonald, Cohen, Stenger, & Carter, 2000; Milham et al., 2001). In addition, recent-no trials from the adapted item recognition task have generated specific neural activity in LIFG compared with other frontal regions (Jonides et al., 1998; Nelson et al., 2003). Recently, several researchers have developed other tasks specifically designed to study the neural basis of selecting a task-relevant internal representation among competing alternatives (Brass & von Cramon, 2004; Zhang, Feng,

Fox, Gao, & Tan, 2004) and found activation localized to LIFG only under conditions of conflict.

Taken together, these findings suggest that LIFG plays an important role in engaging the control mechanisms necessary for resolving representational conflict. It is worth mentioning, however, that representational conflict can arise at numerous possible stages, ranging from internal perceptual representations all the way to conflicting motor-response preparations (e.g., Botvinick et al., 2001). It seems reasonable that, based on a review of the cognitive control literature (e.g., Carter et al., 1998; Dehaene, Posner, & Tucker, 1994; Kerns et al., 2004; Milham et al., 2001; Nelson et al., 2003; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), LIFG and neighboring regions within PFC are responsible for handling internal representational conflict rather than response-based conflict (see Milham et al., 2001). A second frontal lobe region, the anterior cingulate cortex (ACC), appears to be dedicated to detecting response-based conflict. In many cases, internal conflict and re-

sponse conflict go hand in hand; indeed, both PFC and ACC are routinely activated in the Stroop task (e.g., Kerns et al., 2004; A. W. MacDonald et al., 2000; Milham et al., 2001). Some studies, however, have attempted to disentangle the relative contributions of these two regions to response-based and internal conflict resolution (e.g., Milham, Banich, & Barad, 2003; Milham et al., 2001; Nelson et al., 2003). For instance, Nelson et al. suggested that recent-no trials in the item recognition task predominantly generate internal conflict rather than response conflict (i.e., how to characterize the probe letter). In a follow-up study, they tested this hypothesis by comparing these trials with newly designed trials that should induce strong response-based conflict. On these “response-conflict” trials, the current probe letter was not a member of the current set (a “no” response) but was both a member of the set on the previous trial *and* the probe item on that previous trial (a “yes” response). Here, conflict is expected to arise at the response level (because individuals just responded “yes” to the same probe) as well as internally, because the probe is familiar given its recent presentation. Indeed, these trials gen-

erated activation in ACC and LIFG as compared with nonconflict trials, whereas the classic recent-no trials generated the greatest activation in LIFG. This finding corroborates Hamilton and Martin’s (2005) findings for Patient M.L., who, again, performed within the normal range for all response-conflict (e.g., antisaccade) tasks but outside the normal range for tasks requiring internal conflict resolution (see also brain imaging and brain response results of Garavan, Ross, Murphy, Roche, & Stein, 2002; Gehring & Knight, 2000; A. W. MacDonald et al., 2000).

Thus, LIFG is likely to belong to a network of interconnected frontal lobe regions, including ACC, all of which support conflict resolution at multiple levels of representation, from stimulus characterization to response preparation. This hypothesized network is presented and described in Figure 2. Finally, there is some debate regarding whether ACC is solely responsible for detecting response conflict or conflict in general (Botvinick, Cohen, & Carter, 2004; Zhang et al., 2004). What follows, however, does not hinge upon this particular debate, since the focus of this article is on LIFG’s role in modulating and resolving internal conflict.

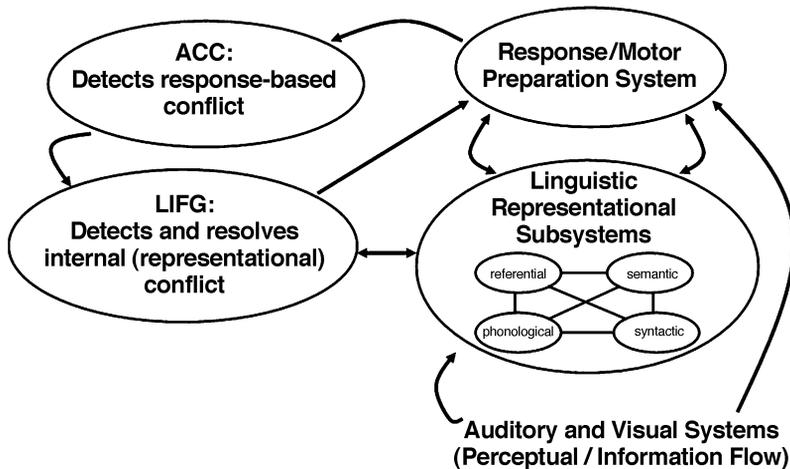


Figure 2. A hypothesized network of frontal lobe regions responsible for cognitive control and conflict resolution, as well as these regions’ relation to hypothesized linguistic subsystems. The linguistic representational system (LRS) gets primary input from sensory subsystems, most notably auditory but also visual (as in the case of reading, gestures, and/or signs). The LRS is constantly monitoring sensory input for linguistically relevant information, which, when present, is automatically characterized at multiple, partially independent levels of representation (phonological, morphological/syntactic, and semantic/logical-form characterizations), all of which serve referential processes. Typically, this process generates consistent characterizations within and across these subsystems. However, when inconsistent solutions occur (either within a subsystem or across subsystems), cognitive control mechanisms may be necessary to bias toward an alternative, more stable solution. The left inferior frontal gyrus (LIFG) is hypothesized to be monitoring and modulating this kind of conflict when it arises. LIFG most likely belongs to a broader network of neighboring systems within prefrontal cortex (PFC) that are all responsible for controlling representational conflict generally. The response/motor preparation system is designed to develop goal-directed behavior, sometimes on the basis of linguistic input (e.g., spoken instructions to act on the world, communicated information that is relevant to immediate goals). Regions of the anterior cingulate cortex (ACC) are responsible for monitoring conflict at the response level. When response conflict is detected, ACC signals PFC regions, including LIFG, to engage in cognitive control.

Role of LIFG in Sentence Processing

As reviewed above, research on cognitive control strongly suggests that LIFG, which includes Broca's area, is responsible for controlling attentional processes necessary for the reliance on task-relevant information. Most notably, in each of the tasks reviewed thus far, little or no syntactic processing is necessary and is very unlikely to occur. Yet, there does exist some compelling brain-imaging evidence that this very region is preferentially engaged in syntactically demanding sentence-processing tasks (Fiebach et al., 2004; Mason et al., 2003). The hypothesis we wish to explore here is that the LIFG activation observed for these tasks in fact reflects another example of this region resolving among competing characterizations of linguistic input, where the characterizations in this case pertain to conflicting syntactic representations. That is, the role of LIFG in sentence processing may be to recover dispreferred parsing options when other, typically reliable sources of information, are currently guiding the parser toward an incorrect syntactic characterization of the input; LIFG may help prevent parsing misinterpretations by reining in prepotent parsing behaviors. In the present section, we address this by simultaneously embedding the function of cognitive control in current psycholinguistic theorizing on sentence comprehension. In so doing, we will offer a picture of how cognitive control and LIFG functioning may also be rooted within relevant aspects of language comprehension.

Psycholinguistic findings: The role of cognitive control in garden-path reanalysis. Most contemporary theories of human sentence processing assume that the recognition of individual words automatically triggers the activation of highly detailed syntactic and semantic information—precompiled “instructions” for how the word combines grammatically with the current (provisional) analysis of the sentence as a whole (e.g., Boland & Cutler, 1996; Kim, Srinivas, & Trueswell, 2002; M. C. MacDonald et al., 1994; Novick, Kim, & Trueswell, 2003; Trueswell & Tanenhaus, 1994). Importantly, this grammatical information can also include information about the likely phrases to expect later in the sentence. The implication here is that word recognition involves far more than activating just the core meaning(s) of a word but also what is often called *argument structure*. Consider what is proposed to be activated automatically during the recognition of the verb in the following fragment:

(1A) The boy gave . . .

The recognition of the verb *give* is presumed to trigger detailed semantic information regarding the number and type of participants involved in the event denoted by the verb—that is, the verb's thematic roles. In this case, an agent (the giver), a theme (the thing being given), and a recipient (the givee) are all expected. Collectively, this information is sometimes referred to as a verb's *thematic grid* (see Carlson & Tanenhaus, 1988). Crucially, syntactic information is also activated regarding the number

and type of phrases expected to occur with the verb, as well as how these phrases map onto its thematic grid. For instance, the past-tense active form of *give* expects a noun phrase (NP) subject, an NP direct object, and a prepositional phrase (PP) indirect object that map onto the agent, theme, and recipient, respectively. In addition, these phrases are expected to be found in that order within the sentence. This syntactic information is often called a verb's *subcategorization frame* (Carlson & Tanenhaus, 1988). Thus, the processing system is prepared for upcoming constituents, such as those that arise in Example 1B.

(1B) The boy gave the present to the girl.

The inclusion of this information as part of what is computed automatically during word recognition means, however, that unique sorts of temporary ambiguity can arise. For instance, the active past-tense form of *give* also allows for an alternative mapping with the same thematic grid (agent, theme, recipient), but a *different* subcategorization frame: an NP subject, an NP indirect object, and an NP direct object in *that* order, which map onto the agent, recipient, and theme, respectively, as shown in Example 1C.

(1C) The boy gave the girl the present.

It is proposed that the processing system deals with this kind of ambiguity via temporary parallelism, which is weighted by frequency or, perhaps more aptly, probability (see Boland & Blodgett, 2001; M. C. MacDonald et al., 1994; Trueswell & Tanenhaus, 1994). If the language comprehension system more often encounters the active past-tense form of *give* in syntactic environments of one particular sort, this will be the preferred subcategorization frame for that verb and, hence, is predicted to be more active.

This account considers word recognition to be the engine that drives much of the initial structuring of comprehension, because the detection of a lexical item includes the relative activation of detailed syntactic and semantic options, which convey additional combinatory meaning to the word itself. Under this view, sentence comprehension is thought to be accomplished by mechanisms that compute both the presence of words and their minimal phrasal environments. Thus, word recognition and phrasal processing are intimately related, such that the presence of a word automatically triggers possible syntactic analyses in a probabilistic fashion.

As just suggested though, the deployment of these mechanisms can provide a rich source of ambiguity, because lexical items appear in a wide array of syntactic environments and, as a result, their recognition activates multiple grammatical options simultaneously. In order to resolve this ambiguity, however, it is assumed that the system relies on multiple sources of evidence from the language—including syntactic and semantic tendencies and relevant contextual information—in order to guide the parser's developing linguistic analyses. This enables the parser to resolve the temporary ambiguity by con-

straining the options given the local input to the system (see Joshi & Schabes, 1997; Kim et al., 2002; M. C. MacDonald et al., 1994; Trueswell & Tanenhaus, 1994). Thus, the most reliable evidence from the language will initially drive parsing decisions. In many cases, this will be lexical information (see Trueswell, Papafragou, & Choi, in press). For most sentences, a conspiracy of evidence will support the correct syntactic analysis. However, on rare occasions, evidence early in a sentence can point toward an incorrect analysis (e.g., when a word is encountered in a dispreferred grammatical environment and the preceding context also supports that analysis). In these garden-path situations, readers and listeners have to re-rank their initial parsing commitments—that is, they must suppress the syntactic analysis that is sustained by the most reliable probabilistic evidence and instead promote alternative, lesser supported syntactic analyses. In such cases, we propose that cognitive control is necessary in order to override automatic, lexically based characterizations of the input.

Behavioral experimental support for this view comes from the study of adult sentence processing, where it has been observed that the resolution of temporary syntactic ambiguity is guided by multiple sources of information, including lexically specific syntactic tendencies and relevant contextual information (Britt, 1994; Garnsey, Pearlmutter, Myers, & Lotocky, 1997; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Novick et al., 2003; Spivey-Knowlton & Sedivy, 1995; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). For instance, Example 2 shows two types of syntactic ambiguity, both of which have been well studied to explore the kinds of information that readers and listeners use to arrive at coherent interpretations in light of temporary indeterminacy.

(2A) The man accepted the money could not be spent yet.

(2B) Put the apple on the towel into the box.

In Example 2A, the postverbal noun phrase *the money* could temporarily be considered the direct object of the verb *accepted* or the subject of an embedded sentence (henceforth the direct object/sentence complement [DO/SC] ambiguity). In Example 2B, the ambiguity centers around the prepositional phrase *on the towel* (the PP-attachment ambiguity). This is because *on the towel* could temporarily “attach” to either the verb *Put* as a goal, indicating where to put the apple, or it could attach to the noun phrase *the apple* as a modifier, indicating which apple needs to be put somewhere in case more than one is present.

Both sentence types tend to induce brief misinterpretations—a garden-path effect—in readers and listeners alike. The reason is that in each case, there is countervailing information between the verb and the grammatical environment in which it is found. *Accept*, for instance, has a strong tendency to appear with direct objects throughout the language, so when readers are faced in-

stead with post-NP evidence like *could not*, they often slow down at this point and sometimes launch a reread of the sentence. This suggests that readers tend to take the NP *the money* initially as the direct object of *accepted* but then revise that commitment when the second verb phrase is encountered. In other words, they adjust their initial characterizations of the input: The dominant (or prepotent) direct-object analysis must be overridden and the sentence-relevant SC interpretation must instead be recovered.⁵ Several studies have observed that at least two evidential sources of information can initially guide readers toward either the DO interpretation of this type of sentence or the correct SC interpretation: (1) whether, throughout the language, the verb statistically tends to take a direct object or a complement phrase (e.g., *accepted* vs. *figured*); and (2) whether the semantic fit of the postverbal NP is plausible (e.g., *the money* vs. *the fire*). In other words, a verb’s subcategorization and thematic role preferences drive readers’ processing commitments, supporting the idea that sentence comprehension is an automatic process driven especially by lexical constraints (e.g., Britt, 1994; Garnsey et al., 1997; Trueswell et al., 1994).

Likewise, the verb *put*, as in Example 2B, strongly prefers a location goal to be present in the sentence, typically in the form of a prepositional phrase. The phrase *on the towel* here satisfies this constraint rather plausibly, and so the parser is encouraged to fill that role when the phrase is encountered. However, the detection of a second prepositional phrase, *into the box*, signals that this initial characterization of the input is incorrect and ultimately needs to be revised. Thus, initial parsing analyses must be re-ranked: The subordinate modifier interpretation for *on the towel* must be promoted above the goal analysis in order for the sentence to be accurately understood. Indeed, both reading and listening studies exploring this type of ambiguity show that verb information strongly influences the parser’s developing linguistic analysis (e.g., Britt, 1994; Spivey-Knowlton & Sedivy, 1995; Tanenhaus et al., 1995). In addition, the garden-path effect observed for the PP-attachment ambiguity can be attenuated by referential contexts that support a modifier analysis—for instance, a visual scene containing two apples (e.g., Novick, Trueswell, January, & Thompson-Schill, 2004; Spivey, Tanenhaus, Eberhard, & Sedivy, 2002; Tanenhaus et al., 1995; Trueswell, Sekerina, Hill, & Logrip, 1999). Referential information, then, is yet another source of evidence on which the parser may rely to help achieve coherent and plausible interpretations by overriding the strong lexical bias (Novick, Trueswell, et al., 2004). Indeed, a recent study that manipulated both verb bias and referential context reveals that these two sources of information interact to guide parsing (Snedeker & Trueswell, 2004).

As a whole, the potency of lexical evidence appears to drive parsing decisions, but when the converging information leads toward an interpretation that is inconsistent with this evidence, other sources of information (e.g.,

referential context and postambiguity information) can be used to rein in initial parsing analyses and to recover alternative ones. Current psycholinguistic theories thus emphasize that when a lexical item is encountered in a local grammatical environment that conflicts with probabilistic expectations, readers and listeners are temporarily garden-pathed and must then revise their initial linguistic analysis so as to recover the intended (and perhaps dispreferred) grammatical characterization of the input. In our estimation, garden-path recovery must involve cognitive control processes, because in these cases “habitual” parsing analyses must be countermanded in order to avoid an incorrect interpretation. This is analogous to conflict resolution in the nonparsing cognitive control tasks discussed earlier (e.g., reading the word rather than naming the ink color, as in the Stroop task). Instead, currently relevant information—which may otherwise be less informative throughout the language (e.g., referential context)—or newly discovered relevant information that was unavailable at the point of ambiguity (i.e., disambiguating evidence like *into the box*), must be promoted to overrule the strong influence of lexical tendencies.

Thus it is our contention, based on the neurocognitive literature on cognitive control, that LIFG detects conflict when multiple characterizations of the linguistic input point toward incompatible interpretations and implements garden-path reanalysis to recover the relevant parse from these discrepant solutions of the input. For instance, in Example 2A above, detection of a second verb phrase (. . . *could not* . . .) is in conflict with the dominant syntactic analysis up to that point but supports a subordinate SC analysis. LIFG is expected to become active in order to reorganize syntactic and semantic patterns away from the dominant analysis and settle into an alternative stable state.

Although one could imagine a number of ways to achieve reanalysis, our thinking is as follows. Upon encountering disambiguating information like *could not* (Example 2A) or *into the box* (Example 2B), the parser has to relax its initial commitment to the analysis that was strongly pursued up to that point (e.g., *the money* as direct object of *accepted*), because the newly discovered information is incompatible with that solution. Then, once this analysis has been suppressed, the parser revises its syntactic characterization of the input to be in accordance with *all* the available evidence, including less reliable linguistic and nonlinguistic patterns (e.g., referential context). This allows the system to settle into a different analysis that better respects the sentence- and situation-relevant information. This way, even though the parser will initially derive an analysis that is guided by a strong and generally reliable linguistic precedent, cognitive control allows such analyses to be overridden in the event that this guidance is rendered ineffective in light of new information.

It follows from this account, then, that increased activation is *not* expected in LIFG for ambiguity generally, but only in cases where the available linguistic evidence supports multiple conflicting parsing characterizations. In particular, LIFG activation should only be observed

when it is necessary to override prepotent parsing analyses to recover a dispreferred but relevant characterization of the input. If, for instance, verb subcategorization and thematic biases do in fact converge on the same ultimate analysis—for example, *The man figured the fire could not . . .*—the words *could not* would not trigger conflict resolution processes and therefore would not activate LIFG. This is because the verb *figured* (unlike *accepted*) “expects” an embedded sentence due to its frequency with one in the language and, here, that probabilistic constraint is satisfied. In addition, even though the verb *figured* also “permits” a direct object (i.e., a second subcategorization frame), *the fire* is a semantically implausible direct object for this verb. Thus, despite the structural ambiguity, two relevant sources of information point strongly toward a single analysis, therefore minimizing conflict and the need for control and resolution processes.

LIFG should, however, be active in other situations of conflict, such as when current semantic analyses conflict with probabilistic syntactic patterns. One case of this is the example *The man accepted the fire . . .*, in which lexicosyntactic (i.e., subcategorization) preferences support a direct object (and hence theme) analysis of the NP *the fire*, but the semantic properties of the NP *the fire* are more compatible with it not being a theme, but rather the start of an embedded clause.

In light of these predictions, we offer an important caveat: As many researchers have noted in the past, Broca’s area within LIFG is a fairly large area of cortex, which includes at least two cytoarchitecturally distinct regions (BAs 44 and 45) and perhaps even further subregions (Amunts et al., 1999). It may very well be, then, that LIFG as a whole is responsible for conflict resolution on tasks that give rise to incompatible representations, but is organized into specialized circuitries depending upon the information types involved. That is, resolution processes for conflicting representations are implemented here but are organized into smaller subregions on the basis of what type of information is being modulated. Logical arguments from information-processing theory could be made that this must be the case. On the other hand, a system that is expected to resolve multiple evidential sources from disparate modalities and information types may be used as an argument against information-specialized circuitry (consider the combinatorial explosion of circuitry for each case of conflict). For this reason, we remain agnostic as to whether subregions within LIFG may engage control in response to specific types of linguistic information such as syntactic reanalysis. Instead, we make the broader claim that LIFG, including Broca’s area, engages conflict resolution processes more generally, which, of course, includes syntactic reanalysis. Exploring the possibility of specialized resolution functions, though, is an important empirical question.

In the remainder of this section, we discuss both brain-imaging and patient data that we believe support some of the predictions we have outlined thus far.

Brain-imaging evidence: The role of LIFG in syntactic reanalysis. An exhaustive review of the neuroimaging research on language comprehension is beyond the scope of this article (but see Kaan & Swaab, 2002). Rather, we focus here on neuroimaging studies that explore the effects of garden-path sentences on neural activity because of the likelihood that conflict resolution processes are required in these tasks. However, surprisingly few such studies have been reported in the literature (Fiebach et al., 2004; Mason et al., 2003; Noppeney & Price, 2004). In accord with our expectations though, LIFG regions have been found to be active during ambiguity resolution, especially when multiple sources of structural evidence are in conflict. In one task (Mason et al., 2003), readers were presented with the PP-attachment ambiguity in both preferred and dispreferred contexts: *The disgusted student threw the book on the ground but picked it up moments later* (preferred) versus *The disgusted student threw the book on the battle but picked it up moments later* (dispreferred). Although both versions are syntactically ambiguous, this “preference” factor was aimed at establishing whether additional brain activity could be measured for the supplementary processing necessary to resolve garden-path sentences with more conflict—that is, because the verb *throw* is biased toward taking a PP location goal like *on the ground*, the dispreferred modifier interpretation will need to be recovered after the dominant analysis is initially pursued. If increased cortical activity is observed, this finding would be consistent with the increased difficulty previously reported during reading time measures for these sorts of stimuli (e.g., Rayner, Carlson, & Frazier, 1983; Taraban & McClelland, 1988). Indeed, the dispreferred sentences took longer to read in this task and also activated LIFG. Presumably, such activation was observed because the sentences were resolved inconsistently with the expected patterns (or “preferences”) of the individual verbs. In other words, when garden-path reanalysis was necessary, LIFG was more heavily recruited.

In addition, Mason et al. (2003) directly compared sentences that contained temporary syntactic ambiguities with those that did not. This second experiment used the main clause/relative clause (MC/RC) ambiguity as illustrated in the four sentences below, which are taken from their stimulus set:

- (3A) The experienced soldiers warned about the dangers conducted the midnight raid.
(ambiguous RC)
- (3B) The experienced soldiers warned about the dangers before the midnight raid.
(ambiguous MC)
- (3C) The experienced soldiers who were told about the dangers conducted the midnight raid.
(unambiguous RC)
- (3D) The experienced soldiers spoke about the dangers before the midnight raid.
(unambiguous MC)

In Examples 3A and 3B, the phrase *warned about the dangers* is temporarily ambiguous between being part of a relative clause (in which case the soldiers are being warned; Example 3A) or a main clause (in which case the soldiers are doing the warning; Example 3B). People prefer the MC interpretation of this phrase because the lexico-syntactic and -semantic evidence supports this analysis and, as a result, readers experience a large garden path when the phrase turns out to be an RC, as in Example 3A (see M. C. MacDonald, 1994). The other conditions (Examples 3B, 3C, and 3D) do not have this strong structural conflict. Indeed, Mason et al. (2003) found LIFG to be more active in the first condition (ambiguous RC; Example 3A) than in the three other conditions. Importantly, LIFG activity was significantly reduced for ambiguous items that were resolved toward the MC analysis (Example 3B, as compared with Example 3A), since there is more linguistic evidence to support this interpretation and thus less conflict.

As we stated earlier, ambiguity itself should not increase activity in LIFG if multiple evidential sources immediately converge on a single analysis. However, Mason et al. (2003) found that ambiguous MC stimuli (Example 3B) show more LIFG activation than unambiguous MC stimuli (Example 3D). They therefore concluded that the mere presence of syntactic ambiguity, even under reduced conflict conditions, generates increased activity in LIFG. We disagree with this interpretation, because another crucial difference exists between the ambiguous MC and unambiguous MC stimuli—namely, a difference in the verbs used in these two conditions (e.g., *warned* vs. *spoke*). For instance, *spoke* was chosen because it unambiguously marks an MC due to its unique passive form (*spoken*). However, an inspection of the materials shows, in our opinion, that most of the ambiguous verbs (e.g., *warned*, *watched*, *dropped*) are verbs that tend to be used transitively, whereas many of the unambiguous verbs are intransitively biased (e.g., *spoke*, *fell*, *giggled*). The presence of a PP (e.g., *about the dangers*) in (Example 3B), then, conflicts with the transitive subcategorization preference of the verb *warn* and indeed partially supports the subordinate RC interpretation (see M. C. MacDonald, 1994, for behavioral evidence). Thus, the ambiguous MC condition, because of the choice of materials, contains considerably more evidential conflict than the unambiguous MC condition.

We also disagree with Mason et al.’s conclusion that their data support a syntax-specific role for LIFG responsible for “the internal generation of abstract syntactic representations” (Mason et al., 2003, p. 1334). In light of the conflict resolution data from nongrammatical cognitive control tasks discussed earlier, which also implicate LIFG activity, we suggest here that the patterns seen in Mason et al. have more to do with resolving conflict that is brought about by linguistic stimuli generally.

In a separate set of brain-imaging studies, Fiebach et al. (2004) explored the time-course of neural activation in response to early-versus-late disambiguation points

for syntactically ambiguous subject- and object-relative sentences in German. In terms of behavior, they observed increased reading times and a greater proportion of errors when disambiguation points came late within a clause generally, indicating that the longer multiple incompatible analyses have to be maintained in WM (i.e., larger garden-path effects), the harder they are to resolve. In addition, late disambiguating conditions gave rise to greater LIFG activity. In other words, when newly discovered disambiguating information comes late—that is, when readers are farther along the garden path, thus pursuing multiple conflicting analyses longer—LIFG is more active than when they pursue a single analysis for a shorter duration.⁶

Of course, our hypotheses about the role of LIFG in sentence processing also make specific predictions for patients with a highly localized lesion to this area. In particular, such patients are expected to have fairly intact language comprehension abilities that diverge from the normal profile for only linguistic material that requires resolution of competing characterizations of the input.⁷ Under the psycholinguistic view of sentence processing that we sketched above, garden-path sentences and other extreme cases of reinterpretation are atypical, since there is usually a conspiracy of evidence (lexicosyntactic, lexicosemantic, referential, and prosodic) collectively pointing toward intended and mutually consistent analyses. Only in cases of strong syntactic conflict do we see the normal system become temporarily unhinged. Thus, a focal lesion to LIFG ought to generate an inability to engage syntactic reanalysis in the face of what would normally be only a temporary misinterpretation—that is, a patient of this sort should be unable to recover a dispreferred parse when one source of evidence must battle against many others (such as the cases discussed in Example 2). Essentially, the patient ought to be too entrenched in the probabilistically dominant syntactic analysis and therefore unable to disengage from the currently unstable state. We also suggest that if the patient's medial frontal lobe is intact, and thus ACC is fully functional, he or she may be able to detect the response conflict and perhaps even recognize when an error is made or about to be made. Nevertheless, the patient should be unable to implement the control necessary to re-rank syntactic representations (or interpretations), ultimately leading to an irrelevant or incorrect analysis of the sentence. Likewise, the patient should not be able to prevent and/or correct such parsing errors. Crucially, however, these patients should be able to comprehend syntactically and semantically complex sentences when the evidence conspires toward the correct analysis.

With this in mind, we now turn to encouraging performance data from patients on a number of production and comprehension tasks and suggest that their patterns are highly relevant to the suppositions we have developed throughout. We begin first with language production tasks in patients with LIFG damage.

Patient observations: Support from production tasks. We have drawn attention to the fact that focal le-

sions to LIFG do not produce the full symptom-complex referred to as Broca's aphasia—the deficits are more restricted, and systematic investigations into the nature of these deficits are still developing. One common symptom, however, among patients with focal lesions to this region is their characteristic lack of verbal fluency. Luria (1973) called this impairment “dynamic aphasia” because its manifestation seemed to intensify in some contexts but fade in others. Such a pattern suggests to us that the problem may be only peripherally related to grammatical abilities per se, and that this waxing and waning of linguistic deficits may be better characterized in broader cognitive terms. In particular, we believe that it may have more to do with the occurrence and resolution of conflict during language-related tasks.

In this vein, Robinson et al. (1998) reported results from a case study of a dynamic aphasic, Patient A.N.G., with an LIFG lesion impinging on Broca's area. A.N.G. was examined on 12 verbal generation tasks that are commonly used among studies exploring components of language production. These tasks are slightly different from the conflict resolution tasks that we have been discussing thus far; nevertheless, we believe that they resemble each other in important ways. In particular, the verbal generation tasks used by Robinson et al., which we will review below, also induce high levels of conflict since they require participants to choose among a number of *equally* acceptable response options generated by the stimuli; that is, no single response option is more compelling than another, given the task. These “underdetermined responding tasks” are analogous to both the Stroop and item recognition tasks in that they also give rise to “multiple incompatible response pathways, resulting in crosstalk during the period between stimulus presentation and response delivery” (Botvinick et al., 2001, p. 628). Further crucial similarities also exist: Previous neuroimaging studies have reported activation of ACC and LIFG during tasks with indeterminate response options (e.g., Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1996; Nathaniel-James & Frith, 2002; Peterson, Fox, Posner, Mintun, & Raichle, 1988; Thompson-Schill et al., 1997; Warburton et al., 1996; see Botvinick et al., 2001, for a comprehensive review). We therefore believe that Robinson's study is an important one to highlight in support of our claim that LIFG plays a crucial role in resolving representational conflict that is brought about by linguistic stimuli.

In one task, Patient A.N.G. was asked to complete unfinished sentences that were designed to vary along a response-predictability continuum, such that the number of underdetermined response options was high in some cases and low in others. Here, this was defined by how predictable a continuation could be, given the setup sentence. For instance, some sentences had low predictability and depicted habitual events (e.g., *The man sat in the chair . . .*), whereas others had relatively high predictability and depicted less habitual events (e.g., *The man sat in the dentist's chair . . .*). The highly constraining context in the predictable conditions alleviated conflict because

there were fewer equally permissible response options; by contrast, conflict was high in the unpredictable cases because the contextual representation did not point to any distinctively compelling response. Thus, it is assumed that the unpredictable condition generated multiple simultaneously active but incompatible responses upon stimulus presentation, whereas the predictable condition was relatively constrained (though, of course, not entirely). In support of this, A.N.G. demonstrated a unique inability to form completions for only the cases that had multiple indeterminate responses—that is, sentences with lower response predictability. On the other hand, for the items with a higher response predictability, she provided plausible continuations for all of the sentences usually within 2 sec—a performance statistically indistinguishable from that of healthy control participants. The authors concluded that for this task, sentence fragments with relatively unconstrained verbal response options proved to be more difficult because of greater interference among possible continuations.

The 11 other production tasks that Robinson et al. (1998) examined—all of which involved stimuli that gave rise to underdetermined responding—ranged from picture and scene descriptions to generating sentences, given a context or single common words. Each of these tasks was controlled to rule out more general explanations regarding difficulty with verbal planning, abstractness, or a failure to deal with linguistic novelty. In all cases, A.N.G.'s deficit was limited to only the conditions in which verbal response options were in conflict, given the stimulus and/or context. The authors therefore reasoned that

verbal response options compete against one another through mutual inhibition. The greater the number of competing verbal response options activated by a stimulus, the greater the amount of inhibition any individual verbal response option would receive from its competitors. When individual verbal response options are being inhibited by multiple competing verbal response options, there is less probability of one becoming dominant. However, an executive controlling system might be able to resolve the conflict by allowing one verbal response option to become dominant. It is proposed that A.N.G. had suffered disruption to such an executive controlling system. (Robinson et al., 1998, p. 86)

This explanation is consistent with our hypotheses. For production tasks involving conflict resolution, LIFG is involved in resolving representational interference when it gives rise to several mutually exclusive responses. A.N.G., whose lesion is in LIFG, therefore cannot recover from the instability that arises from multiple conflicting verbal responses and, as a result, neglects to stably settle on a single one. We would thus predict that this patient would behave similarly to Patients R.C. (Thompson-Schill et al., 2002) and M.L. (Hamilton & Martin, 2005) on internal conflict resolution tasks involving competing linguistic representations (e.g., recent-no trials for item recognition and Stroop task, etc.), because of the need for control processes to help reconcile a relevant charac-

terization of the input. Furthermore, with respect to sentence processing, we would also predict a failure to revise initial parsing commitments for garden-path comprehension tasks during which incompatible syntactic analyses arise. Again, common to all of these tasks is the need to direct response processes toward a stable solution, which is achieved by the implementation of error-related performance monitoring and subsequent cognitive control.

Other patient evidence from language production tasks that support our view comes from confrontation naming tasks in which both healthy adults and brain-damaged patients are asked to generate a word, given only a picture stimulus. Such a task can be designed to maximize conflict by presenting pictures in semantically related blocks. When this is done, healthy adult speakers demonstrate reliable patterns of proactive interference (Damian, Vigliocco, & Levelt, 2001; Vitkovitch & Humphreys, 1991), implicating conflict resolution, because interference results only as a function of increasing familiarity-based alternatives—that is, as the number of intervening semantically related items rises (see also Thompson-Schill et al., 1997, who reported LIFG activation in healthy adults performing a similar task; and Thompson-Schill et al., 1998, who suggested that LIFG is necessary for such a task). As in the conflict resolution tasks discussed earlier, cognitive control must therefore be implemented in order to promote only the trial-relevant information in the face of semantically related but otherwise irrelevant stimulus characterizations. Recently, the interference effect for this task was reported to be outside the normal range for a patient with damage to LIFG and Broca's area in particular (Wilshire & McCarthy, 2002).

Patient observations: Support from comprehension tasks. With respect to the role of LIFG and cognitive control in comprehension, enticing results exist in the lexical ambiguity literature. Given our view that LIFG implements cognitive control to resolve representational conflict, it is reasonable to expect this region to be active during the recovery of a probabilistically dispreferred sense of an ambiguous word (or homograph) like *bank*, which has two distinct meanings (a financial institution and a river's edge). This is relevant to discussions of the garden-path recovery aspects of syntactic ambiguity resolution—and indeed to the nonsyntactic conflict resolution tasks discussed earlier—because all of these tasks require the ability to coordinate among multiple analyses and characterize the input according to task-relevant information. Because the word *bank*, for instance, is more frequently associated with the financial institution, this regularized characterization has to be overruled when the intended interpretation is the river's edge. Again, this should be the case even when recovery of a different syntactic analysis is not required (e.g., *The accountant walked to the bank and tossed his fishing line into the water*), but only when countervailing information supports incompatible linguistic representations.

In support of this, Metzler (2001) has suggested that the cognitive control processes related to homograph resolution reside generally in left PFC. Compared with

healthy controls and patients with right-hemisphere prefrontal damage, patients with left or bilateral PFC damage failed to show facilitation when asked to name the third word in a sequence of semantically related words containing one lexical ambiguity (e.g., *girl–date–boy*) as opposed to a sequence of items in which the homographs were replaced by unambiguous words (e.g., *girl–rendezvous–boy*). This suggests a deficit in the ability to select a context-appropriate meaning in the presence of mutually exclusive alternatives; that is, multiple incompatible representations have been detected, but the system is unable to reorganize itself in order to settle on the appropriate one. As we have indicated, contemporary theories of lexical and syntactic ambiguity resolution suggest many processing commonalities (e.g., M. C. MacDonald et al., 1994). Of course, the patients studied in this experiment had somewhat extensive damage to left PFC; they did not necessarily have restricted lesions to LIFG specifically. Nevertheless, the results are highly suggestive and are in accordance with general views of PFC functioning regarding its role in conflict resolution and guiding attentional control (Miller & Cohen, 2001). Future studies of patients with more restricted and common lesion sites will be necessary to further pin down the particular role of LIFG in homograph resolution.

Similarly, it will be important to examine garden-path recovery in patients of this sort, akin to experiments that traditionally comprise the sentence comprehension literature of healthy adults and young children. Indeed, we have recently tested Patient N.J. (who, as mentioned above, has a localized lesion to LIFG) in a sentence comprehension task involving syntactic ambiguity. As predicted, he demonstrated a selective impairment in recovering from garden paths (Novick, January, et al., 2004). The existing literature has not focused on garden-path sentences, but instead on related phenomena pertaining to passives as well as the comprehension of long-distance dependencies (a form of syntactic ambiguity). These studies have generated a range of conflicting findings, primarily, we would argue, because selection criteria for the patients has been somewhat inconsistent: some based on lesion site, and others based on symptom patterns (see Caplan, 1995). Thus, it is necessary to appropriately classify patients in order to establish our proposed link between LIFG and cognitive control and conflict resolution problems.

Individual Differences in Cognitive Control and Language Abilities

Comparisons of brain-damaged patients' performance with that of healthy individuals can be considered an extreme case of individual variation in language processing and cognitive control abilities. Thus, our final hypothesis is that *normal* variation in cognitive control abilities within healthy populations should be related to relevant sentence comprehension abilities as well. In particular, measurable differences among normal individuals in cognitive control abilities should positively correlate

with individual variation in garden-path recovery abilities. Below, we review the evidence to date on this issue and relate these findings to the literature on variation in WM capacity (see Caplan & Waters, 2002; Just & Carpenter, 1992; Miyake, Just, & Carpenter, 1994). In particular, we suggest that the most widely used capacity tasks can and should be unpacked into component processes that involve nonmnemonic functions such as resolving interference. In addition, the existence of a relationship between cognitive control and parsing abilities should be manifested in development, such that maturational changes in cognitive control abilities in young children (such as those documented in Diamond & Doar, 1989, and Diamond & Taylor, 1997) ought to go hand in hand with garden-path recovery abilities. Below, we will also review some tantalizing evidence in support of this hypothesis.

Individual differences: Sentence processing and cognitive control. In a large-scale study of individual differences among healthy adults, Mendelsohn (2002) attempted to relate general measures of cognitive control to sentence comprehension abilities.⁸ Control abilities were assessed using three tasks, the Wisconsin Card Sorting Task, the antisaccade task, and a verbal sorting task (which was developed by Mendelsohn), as well as a measure of verbal capacity—that is, the reading span task (Daneman & Carpenter, 1980). The Wisconsin Card Sorting and antisaccade tasks have typically been used to explore an individual's general ability to override automatic response processes. Mendelsohn suggested that her verbal sorting task—a linguistic analog to the Wisconsin Card Sorting Task—ought to tap control abilities specifically pertaining to linguistic representations, and thus may correlate most strongly with lexical ambiguity resolution and garden-path recovery abilities. This task required participants to sort words based on their syntactic, semantic, and phonological properties instead of the more traditional color, shape, and number. As with the card sorting task, participants' sorting behavior was given feedback with each categorization, but the experimenter adjusted the rules periodically without informing the participants that they were about to change. As a result, the verbal sorting task often required participants to override a regularized process on the basis of linguistic representations.

As a whole, performance on the verbal sorting task was indeed the best predictor of an individual's ability to reject the contextually irrelevant (but dominant) meaning of a homograph like *bank*. Mendelsohn (2002) thus concluded that language-related measures of control are better predictors of performance on lexical ambiguity resolution tasks than those less related to language (e.g., the antisaccade task). This result is reminiscent of work done by Gernsbacher and colleagues (Gernsbacher, 1993; Gernsbacher & Robertson, 1995), who found that less skilled readers are slower than good readers both to reject and accept the discourse-inappropriate meanings of ambiguous words. According to these findings, the abil-

ity to resolve between two competing lexical representations is related to greater experience with one's language. This idea coincides with our account because it suggests that linguistic exposure, which presumably enables the tracking and activation of multiple evidential sources, can greatly influence one's ability to reorganize linguistic patterns.

In a second experiment found in Mendelsohn (2002), participants read DO/SC ambiguities like Example 2A above, repeated here as Example 4:

- (4) The man accepted the money could not be spent yet.

They were then given follow-up comprehension questions such as *Did the man accept the money?* Every item resolved with the embedded clause interpretation rather than with the DO interpretation, so the correct response to these questions was always "no," because *the money*, for instance, is not the direct object (and therefore is not being accepted). Indeed, both RT and accuracy measures for these questions are indicative of an individual's garden-path recovery abilities, because they gauge whether the dominant syntactic analysis "lingers" and whether full reanalysis has taken place (see, e.g., Ferreira, Christianson, & Hollingworth, 2001). Performance on this task was measured by the time that participants took to reject the interpretation that corresponded to the dominant sentence structure for the verb (which was always the DO structure). When the various WM and control tasks were entered into multiple regressions, it was found that performance on the garden-path recovery task was predicted by two language-related tasks: the verbal WM task and Mendelsohn's verbal sorting task, which, again, tapped control abilities unique to linguistic representations. When the reading span and the verbal sorting task were both entered into stepwise regressions along with all of the other tasks (e.g., antisaccade, etc.) to compare their predictive value for garden-path recovery abilities, the verbal sorting task was the first factor to enter the regression analysis. One interpretation that Mendelsohn offered for this finding is that the verbal sorting task is the best predictor of garden-path recovery performance. In other words, Mendelsohn suggests that an individual's specific ability to override habitual language-related processes was the best predictor of individual variation in sentence-processing tasks that require syntactic reanalysis.

Taken together, Mendelsohn's (2002) findings suggest that a relationship does indeed exist between cognitive control and garden-path recovery abilities. Our group has recently collected further evidence in support of this claim that more directly relates the sentence-processing literature to the neurocognitive literature on cognitive control (Novick, Trueswell, et al., 2004). In particular, we have found that individual variation in the ability to revise parsing commitments during garden-path tasks is quite similar across-modality (spoken vs. written sentence comprehension) and even ambiguity type (PP-attachment vs. DO/SC ambiguity). Moreover, these abil-

ities appear to be related to neurocognitive assessments of conflict resolution abilities in tasks such as the modified item recognition task.

Importantly, there have been other proposals regarding the relationship between general cognitive abilities and sentence comprehension abilities (e.g., Baddeley, 1986; Caplan & Waters, 2002; Gibson, 1998; Lewis, 1996; M. C. MacDonald & Christiansen, 2002; Roberts & Gibson, 2002), which we believe are relevant to this discussion. Most notably, several researchers have explored a possible relationship between WM capacity and syntactic ambiguity resolution (e.g., Just & Carpenter, 1992; Miyake et al., 1994; Waters & Caplan, 1996). One particularly well-known account suggests that the number of parses entertained at any given moment is restricted by a limited availability of activation resources in WM (Just & Carpenter, 1992) and/or that the extent to which evidential sources beyond syntax are used to guide parsing commitments also depends on the availability of these resources (see also Just, Carpenter, & Keller, 1996).

Much of the evidence offered in favor of this view has come from studies of individual differences in the normal adult population. For instance, in Just and Carpenter (1992), the Daneman and Carpenter (1980) reading span task was used to assess an individual's verbal WM capacity and classify him or her as either high or low span. The reading span consists of having individuals read aloud increasingly large sets of sentences and then recall the last word of each of these sentences. Individuals who perform well on this task (high-span participants) were more likely to (1) use nonsyntactic information (such as plausibility) during the parsing of ambiguous and unambiguous structures and (2) have less difficulty reading structurally complex constructions, such as object-relative clauses (*The actor who the producer introduced complimented the director*). Just and Carpenter suggested that these differences in reading times reflect differences in a domain-general resource within verbal WM.

There have, however, been criticisms of Just and Carpenter's (1992) individual differences account (e.g., M. C. MacDonald & Christiansen, 2002; Waters & Caplan, 1996). One argument, which we find particularly compelling, comes from M. C. MacDonald and Christiansen, who suggest that the distinction that Just and Carpenter draw between their reading span task and language-processing tasks is artificial and that both tasks are "simply different measures of language processing skill" (M. C. MacDonald & Christiansen, 2002, p. 36). That is, given that both tasks involve the processing of sentences, it may not be surprising that they relate as they do across individuals.

Indeed, we strongly suspect that some aspects of the relationship between the reading span measure and sentence-processing measures simply reflects differences in reading experience, as M. C. MacDonald and Christiansen (2002) suggest. We also suspect, however, that insofar as the Daneman and Carpenter (1980) reading span task taps general processing abilities, it has conflated the notions

of capacity and cognitive control processes related to conflict resolution. D'Esposito and Postle (1999) argue that verbal WM resources involve nonmnemonic capacity, which involves the ability to select among competing alternatives—an ability necessary for some tasks of WM and sentence comprehension. The Daneman and Carpenter task, relevantly, requires considerable cognitive control abilities because participants must selectively attend to the last word of the sentence while at the same time incorporating it into ongoing interpretive processes.

Relevant to this explanation, it has been observed that slight modifications to the reading span task, which we believe decrease control abilities, result in a task that no longer predicts individual variation in syntactic ambiguity resolution (Clifton et al., 2003). In particular, participants in the modified span task were asked to read sentences each of which was followed by an unrelated word (e.g., *The tree fell with a loud crash. SOCKS*) and to later recall these unrelated words rather than the last word of each sentence as in the Daneman and Carpenter (1980) task. This new task arguably decreases demands on competition and interference because the sentence is now independent of the memorized item. Interestingly, this slight modification then resulted in a failure to predict which subjects would have trouble resolving ambiguity (contra Just & Carpenter, 1992). At the very least, this finding highlights that the classic Daneman and Carpenter task may conflate capacity and control abilities in a way that is relevant to components of sentence processing.

Neuroanatomical development and its relationship to sentence comprehension. It is reasonably well documented that the human PFC, including LIFG, is among the last neuroanatomical regions to mature (e.g., Huttenlocher & Dabholkar, 1997; Pribram, 1997). Although synaptic formation has been reported to develop prenatally in many cortical areas including PFC, synaptic density in PFC regions increases more slowly than in other brain areas, often well into infancy (Huttenlocher & Dabholkar, 1997). Furthermore, net synaptic growth and myelin formation in PFC continues to occur well into mid- or late adolescence, whereas this phase may be completed just prior to the teenage years in other regions (e.g., auditory cortex; cf. Huttenlocher & Dabholkar, 1997). Thus, the time-course of neuroanatomical growth in PFC appears to lag from the earliest stages of development, affecting both the speed of neurotransmission and its synaptic connections to other cortical regions. In terms of the functional consequences of this maturational delay, many researchers have suggested that specific cortical underdevelopment in prefrontal systems may be responsible for the slow progression of cognitive control abilities on tasks such as the Stroop task, the go/no-go task (e.g., Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002), delayed-response tasks (Diamond & Doar, 1989), and tasks of selective attention (Luciana & Nelson, 1998; Pearson & Lane, 1991). On these tasks, young children's behavioral performance indicates reliably measurable delays in implementing control compared with older children and adults.

These observations, in conjunction with our neurofunctional account of sentence processing, should predict a developmental progression in sentence comprehension in which garden-path recovery abilities are delayed. Indeed, our own research group has found that young children have difficulty recovering from an initial misinterpretation of a temporary syntactic ambiguity (e.g., Hurewitz, Brown-Schmidt, Thorpe, Gleitman, & Trueswell, 2001; Trueswell et al., 1999). These studies use a world-situated task in which 5- and 8-year-olds respond to spoken instructions to move stuffed toys around a platform. In order to respond, participants have to rapidly coordinate the relevant lexical information from the instructions with contextual and referential information from the visual scene. As mentioned previously, this design allows for insight into the multiple sources of evidence (e.g., lexical, referential) that people use to guide parsing decisions and, moreover, how they use this information when faced with a garden path.

In one study testing young children and adults, Trueswell et al. (1999) maximized representational conflict by manipulating referential scenes and syntactic ambiguity to either facilitate parsing decisions in helpful, felicitous conditions, or to encourage garden paths in others. Critical constructions contained child-friendly versions of the temporary PP-attachment ambiguity in Example 2B, repeated here in Example 5.

(5A) Put the frog on the napkin into the box.
(ambiguous)

(5B) Put the frog that's on the napkin into the box.
(unambiguous)

As expected, adults have a very strong preference to interpret *on the napkin* as a goal, because the verb *Put* takes a goal theme, which is almost always indicated syntactically as a PP headed by either *on* or *in*. Unambiguous versions (Example 5B) eliminate the garden path and therefore strongly support the modifier interpretation. Without going into the details here, eye movements and action patterns in this and the earlier Tanenhaus et al. (1995) study suggest that adults and older children temporarily consider the goal interpretation of *on the napkin* and then quickly revise that interpretation upon hearing *into the box*. Referential scenes that supported the intended modifier interpretation of *on the napkin* (e.g., two frogs, one on a napkin, one on a plate) further reduced temporary consideration of the goal analysis (see also Novick, Trueswell, et al., 2004).

Five-year-olds, on the other hand, demonstrated a very different pattern: They frequently committed to a goal interpretation regardless of context; that is, they looked to an unoccupied napkin in the scene upon hearing the phrase *on the napkin* and often failed to revise this commitment by ultimately moving a frog to this napkin as well. Figure 3 illustrates the difference between adults and 5-year-olds in their ability to revise initial syntactic commitments: children's rate of incorrect actions is roughly 55%, regardless of referential scene. That is,

they frequently made errors involving the incorrect goal. The data suggest that children pursued the interpretation consistent with the verb's dominant subcategorization preferences (*put*) and had specific difficulty reconstructing this syntactic characterization even after the rest of the utterance had unfolded. To us, this reveals an inability to flexibly re-rank parsing commitments when a new situation-relevant characterization of the input becomes necessary. By contrast, adults never failed to revise in light of referential and/or disambiguating evidence. Importantly, unambiguous instructions (Example 5B) yielded nearly 100% modifier interpretations in all age groups, including 5-year-olds, suggesting that their difficulty is anchored in garden-path recovery per se and not in the length or syntactic complexity of the sentence. Indeed, while young children's syntactic representations and processing abilities may not be lagging developmentally—as reflected by their adult-like performance on syntactically complex yet unambiguous constructions—underdeveloped prefrontal systems may be responsible for their inability to reorganize these representations, as evidenced by their poor garden-path recovery abilities.

Thus, a logical reason why 5-year-olds do not pattern with older children and adults may be the difference in cortical maturity, which may also conspire with the informativeness of the linguistic evidence. That is, the lexical reliability that the verb *put* will take a goal is considerably stronger than how reliable a speaker is to modify a referent in one particular way (consider, e.g., *the frog on the napkin*, *the green frog*, *the frog without sunglasses*). As a result, young children become deeply rooted in the most evidential source of information and therefore develop “habitual” or automatic parsing analyses (e.g., the

distribution of *Put . . . on . . .* throughout the language is easy to track, and likely indicates an upcoming goal). If LIFG engages cognitive control processes that are necessary to promote lesser supported syntactic analyses (e.g., *Put . . . on the napkin* characterized as a modifier), it follows that its relative underdevelopment would result in such an inability to revise initial parsing commitments. Similarly, we would predict, of course, the same “child-like” parsing patterns for patients with focal damage to this region, which we have confirmed experimentally (see above). We would also predict that these developmental delays in the ability to revise would not be limited to syntactic material. Indeed, several studies have confirmed that young children have similar problems overriding the dominant meaning of homographs—for example, interpreting *bat* as referring to the animal even in a discussion of baseball (see, e.g., Campbell & Bowe, 1983; Doherty, 2004; Mazzocco, 1997).

Summary and Future Experimental Directions

The current neurocognitive literature on cognitive control and the psycholinguistic literature on sentence comprehension lend support to the theoretical account we have offered. Brain-imaging research suggests an important role for LIFG when syntactic representations conflict during ambiguity resolution tasks (Mason et al., 2003). These same regions are active in brain-imaging studies of nonsyntactic cognitive control when representational conflict is also known to be occurring (Jonides et al., 1998; Nelson et al., 2003). Localized lesions to LIFG appear to cause deficits in a range of conflict-resolution tasks that require engaging control to either override automatic processes or select a response among

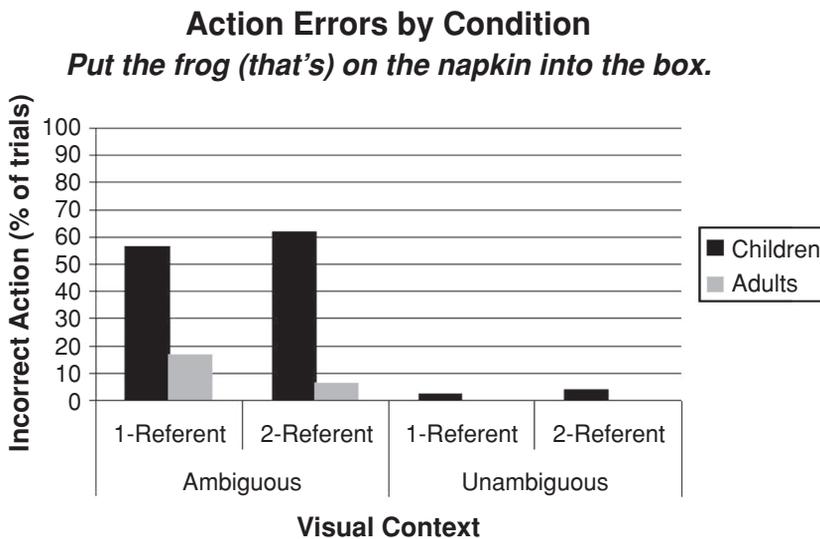


Figure 3. Percentage of trials in which objects (e.g., toy frogs) were moved incorrectly as a function of ambiguity and visual context (1- vs. 2-frog scenes). Five-year-olds demonstrated reliable patterns of errors, interpreting phrases like . . . *on the napkin* . . . to mean destination goals rather than restrictive modifiers regardless of referential scene (data from Trueswell et al., 1999).

multiple indeterminate options (e.g., Hamilton & Martin, 2005; Robinson et al., 1998; Thompson-Schill et al., 2002). Within normal populations, individual variation in the ability to deal with conflict in linguistic (though importantly, nonsyntactic) tasks appears to be systematically related to garden-path recovery in sentence processing (Mendelsohn, 2002). Obviously, however, none of these experiments were designed to test specifically the theory we have sketched here and thus can be viewed only as encouraging support for our account. We therefore believe it is important to experimentally explore the relation between cognitive control and conflict resolution under relevant parsing conditions.

First, it is important that brain-imaging work on language comprehension begin to focus more closely on the garden-path recovery aspects of syntactic ambiguity resolution, especially given that the mechanisms underlying these processes have been heavily studied behaviorally and are now becoming relatively well understood. Given our account, it is urgent that fMRI research be conducted in which, within the same individual, observations are made about abilities pertaining to conflict resolution in both parsing and nonparsing tasks. The strongest prediction would be that LIFG activation patterns are identical for recent-no trials in the item recognition task (e.g., Jonides et al., 1998) or incongruent trials in the Stroop task, and for conditions of garden-pathing in sentence comprehension. It is possible that specific differences within LIFG will arise, which can be used to further refine an account of the processes carried out in this region. Imaging studies of cognitive control tasks involving other sorts of conflicting representations (e.g., a spatial version of the item recognition task), and motor response override (e.g., antisaccade) tasks should also be conducted to further refine the cortical distinctions within internal conflict, and compare these activation patterns with those for tasks of response-based conflict.

Second, studies of impaired sentence comprehension abilities need to be more focused in their assessment of lesion localization and behavioral abilities related to conflict resolution. In particular, restricted lesions to LIFG should not only produce specific difficulty with conflict in tasks requiring cognitive control, but also the ability to recover from garden-path sentences. Again, we have recently found evidence in support of this prediction (Novick, January, et al., 2004).

Third, studies attempting to account for individual variation in sentence-processing abilities need to provide more focused cognitive assessments of control functions, including conflict resolution abilities. These assessments, if possible, need to involve both syntactic and nonsyntactic tasks. In addition, in light of mounting evidence that performance on WM tasks is affected by dissociable mnemonic and nonmnemonic processes, efforts to relate sentence processing to WM should reflect these distinctions. Our group has begun to explore these issues experimentally (Novick, Trueswell, et al., 2004).

Fourth, developmental studies of language need to focus more on the dynamics of its use (see, e.g., Trueswell & Gleitman, 2004). With the advent of eye movement techniques, it is now possible to study children's garden-path recovery abilities in real time. Neuroanatomical development of frontal lobe systems may play an important role in the development of these abilities. Limited ability to recover from garden paths may influence language learning itself and provides an opportunity to examine theories regarding the constraints that processing limitations place on learning (Newport, 1990). Experimentation along these lines will require the development of child-appropriate measures of cognitive control abilities.

In sum, we have sketched some fairly specific hypotheses that follow from our account, and we have reviewed the existing experimental evidence that we believe supports these hypotheses. Mostly, we hope to have provided a roadmap for future research that bridges neurocognitive and neurolinguistic research, especially as it pertains to frontal systems. One important aspect of our account, we believe, is that it is motivated by a fairly detailed model of sentence processing derived from a large body of behavioral research. Indeed, we think that most progress has been made in neurocognitive and neurolinguistic research when a detailed processing perspective has been adopted. For instance, it is now possible from the psycholinguistic literature to make fairly specific predictions about the conditions under which linguistic stimuli generate conflicting analyses of the input, which can be used to test neurolinguistic accounts of language impairment.

Clearly, however, further theory development is also necessary. An important step in this endeavor will be to further define the notion of conflict beyond internal or response-based conflict that may also be occurring. For instance, although language comprehension processes are fairly complex, a theoretical framework of some detail is offered within psycholinguistics regarding the levels of representation at which conflict can arise. To take just one example, we have said little about nonsyntactic referential ambiguity, which is also quite common in language. For example, if one is told to "pick up the toy horse that's wearing the red tie," this linguistic input can generate substantial referential (but not syntactic) conflict when said in the context of two toy horses, one wearing a red tie and a blue jacket and the other wearing a red jacket and a blue tie. This is likely akin to the representational conflict that we have discussed here.

We believe that an opportunity now exists to bridge several lines of research that collectively point to an important role for cognitive control in sentence comprehension. In particular, drawing connections between the brain-imaging literature on conflict resolution and the psycholinguistic literature on real-time sentence processing offers new insight into the anatomical contributions of LIFG, including Broca's area, in syntactic processing. Ultimately, the development of our understanding of the functional-anatomical correspondence between

Broca's area and sentence comprehension will have putative implications for language use broadly defined, particularly if, as we have asserted here, the correspondence is characterized by high-level processes like controlling behavior under conditions of conflict.

REFERENCES

- AMUNTS, K., SCHLEICHER, A., BÜRGE, U., MOHLBERG, H., UYLINGS, H. B. M., & ZILLES, K. (1999). Broca's region revisited: Cytoarchitecture and intersubject variability. *Journal of Comparative Neurology*, **412**, 319-341.
- BADDELEY, A. [D.] (1986). *Working memory*. New York: Oxford University Press.
- BOLAND, J. E., & BLODGETT, A. (2001). Understanding the constraints on syntactic generation: Lexical bias and discourse congruency effects on eye movements. *Journal of Memory & Language*, **45**, 391-411.
- BOLAND, J. E., & CUTLER, A. (1996). Interaction with autonomy: Multiple output models and the inadequacy of the Great Divide. *Cognition*, **58**, 309-320.
- BOTVINICK, M. M., BRAVER, T. S., BARCH, D. M., CARTER, C. S., & COHEN, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, **108**, 624-652.
- BOTVINICK, M. M., COHEN, J. D., & CARTER, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, **8**, 539-546.
- BRASS, M., & VON CRAMON, D. Y. (2004). Selection for cognitive control: A functional magnetic resonance imaging study on the selection of task-relevant information. *Journal of Neuroscience*, **24**, 8847-8852.
- BRITT, M. A. (1994). The interaction of referential ambiguity and argument structure in the parsing of prepositional phrases. *Journal of Memory & Language*, **33**, 251-283.
- BROCA, P. P. (1861). Loss of speech, chronic softening and partial destruction of the anterior left lobe of the brain (Christopher D. Green, Trans.). Retrieved September 10, 2003, from <http://psychclassics.yorku.ca>. *Bulletin de la Société Anthropologique*, **2**, 235-238.
- BUNGE, S. A., DUDUKOVIC, N. M., THOMASON, M. E., VAIDYA, C. J., & GABRIELI, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, **33**, 1-11.
- CAMPBELL, R. N., & BOWE, T. (1983). Text and context in early language comprehension. In M. Donaldson, R. Grieve, & C. Pratt (Eds.), *Early childhood development and education* (pp. 115-126). Oxford: Blackwell.
- CAPLAN, D. (1995). Issues arising in contemporary studies of disorders of syntactic processing in sentence comprehension in agrammatic patients. *Brain & Language*, **50**, 325-338.
- CAPLAN, D., ALPERT, N., WATERS, G., & OLIVIERI, A. (2000). Activation of Broca's area by syntactic processing under conditions of concurrent articulation. *Human Brain Mapping*, **9**, 65-71.
- CAPLAN, D., & WATERS, G. (2002). Working memory and connectionist models of parsing: A reply to MacDonald and Christiansen (2002). *Psychological Review*, **109**, 66-74.
- CARLSON, G. N., & TANENHAUS, M. K. (1988). Thematic roles and language comprehension. In W. Wilkins (Ed.), *Syntax and semantics: Vol. 21. Thematic relations* (pp. 263-289). London: Academic Press.
- CARTER, C. S., BRAVER, T. S., BARCH, D. M., BOTVINICK, M. M., NOLL, D., & COHEN, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science*, **280**, 747-749.
- CLIFTON, C., TRAXLER, M. J., MOHAMED, M. T., WILLIAMS, R. S., MORRIS, R. K., & RAYNER, K. (2003). The use of thematic role information in parsing: Syntactic processing autonomy revisited. *Journal of Memory & Language*, **49**, 317-334.
- DAMIAN, M. F., VIGLIOCO, G., & LEVELT, W. J. (2001). Effects of semantic context in the naming of pictures and words. *Cognition*, **81**, 77-86.
- DANEMAN, M., & CARPENTER, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning & Verbal Behavior*, **19**, 450-466.
- DEHAENE, S., POSNER, M. I., & TUCKER, D. M. (1994). Localization of a neural system for error detection and compensation. *Science*, **5**, 303-305.
- D'ESPOSITO, M., & POSTLE, B. R. (1999). The dependence of span and delayed-response performance on prefrontal cortex. *Neuropsychologia*, **37**, 1303-1315.
- DIAMOND, A., & DOAR, B. (1989). The performance of human infants on a measure of frontal cortex function, the delayed response task. *Developmental Psychobiology*, **22**, 271-294.
- DIAMOND, A., & TAYLOR, C. (1997). Development of an aspect of executive control: Development of the abilities to remember what I said and to "Do as I say, not as I do." *Developmental Psychobiology*, **29**, 315-334.
- DICK, F., BATES, E., WULFECK, B., UTMAN, J., DRONKERS, N., & GERNSBACHER, M. A. (2001). Language deficits, localization, and grammar: Evidence for a distributive model of language breakdown in aphasic patients and neurologically intact individuals. *Psychological Review*, **108**, 759-788.
- DOHERTY, M. J. (2004). Children's difficulty in learning homonyms. *Journal of Child Language*, **31**, 203-214.
- DRONKERS, N. F., WILKINS, D. P., VAN VALIN, R. D., JR., REDFERN, B. B., & JAEGER, J. J. (2004). Lesion analysis of the brain areas involved in language comprehension. *Cognition*, **92**, 145-177.
- DURSTON, S., THOMAS, K. M., YANG, Y., ULUĞ, A. M., ZIMMERMAN, R. D., & CASEY, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, **5**, F9-F16.
- FERREIRA, F., CHRISTIANSON, K., & HOLLINGWORTH, A. (2001). Misinterpretations of garden-path sentences: Implications for models of reanalysis. *Journal of Psycholinguistic Research*, **30**, 3-20.
- FERREIRA, F., & HENDERSON, J. M. (1990). The use of verb information in syntactic parsing: A comparison of evidence from eye movements and self-paced word-by-word reading. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **16**, 555-568.
- FIEBACH, C. J., VOS, S. H., & FRIEDERICI, A. D. (2004). Neural correlates of syntactic ambiguity in sentence comprehension for low and high span readers. *Journal of Cognitive Neuroscience*, **16**, 1562-1575.
- FLETCHER, P. C., SHALLICE, T., FRITH, C. D., FRACKOWIAK, R. S., & DOLAN, R. J. (1996). Brain activity during memory retrieval: The influence of imagery and semantic cueing. *Brain*, **119**, 1587-1596.
- GARAVAN, H., ROSS, T. J., MURPHY, K., ROCHE, R. A. P., & STEIN, E. A. (2002). Dissociable executive functions in the dynamic control of behavior: Inhibition, error detection, and correction. *NeuroImage*, **17**, 1820-1829.
- GARNSEY, S. M., PEARLMUTTER, N. J., MYERS, E., & LOTOCKY, M. A. (1997). The contributions of verb bias and plausibility to the comprehension of temporarily ambiguous sentences. *Journal of Memory & Language*, **37**, 58-93.
- GEHRING, W. J., & KNIGHT, R. T. (2000). Prefrontal-cingulate interactions in action monitoring. *Nature Reviews Neuroscience*, **3**, 516-520.
- GERNSBACHER, M. A. (1993). Less skilled readers have less efficient suppression mechanisms. *Psychological Science*, **4**, 294-298.
- GERNSBACHER, M. A., & ROBERTSON, R. (1995). Reading skill and suppression revisited. *Psychological Science*, **6**, 165-169.
- GIBSON, E. (1998). Linguistic complexity: Locality of syntactic dependencies. *Cognition*, **68**, 1-76.
- GRODZINSKY, Y. (2000). The neurology of syntax: Language use without Broca's area. *Behavioral & Brain Sciences*, **23**, 1-71.
- HAGOORT, P. (2003). *How the brain solves the binding problem for language*. Manuscript from a position paper presented at the 9th Annual Conference on Architectures and Mechanisms for Language Processing, Glasgow, Scotland.
- HAGOORT, P., WASSENAAR, M., & BROWN, C. (2003). Real-time semantic compensation in patients with agrammatic comprehension: Electrophysiological evidence for multiple-route plasticity. *Proceedings of the National Academy of Sciences*, **100**, 4340-4345.
- HAMILTON, A. C., & MARTIN, R. C. (2005). Dissociations among tasks involving inhibition: A single-case study. *Cognitive, Affective, & Behavioral Neuroscience*, **5**, 1-13.
- HUREWITZ, F., BROWN-SCHMIDT, S., THORPE, K., GLEITMAN, L. R., &

- TRUESWELL, J. C. (2001). One frog, two frog, red frog, blue frog: Factors affecting children's syntactic choices in production and comprehension. *Journal of Psycholinguistic Research*, **29**, 597-626.
- HUTTENLOCHER, P. R., & DABHOLKAR, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology*, **387**, 167-178.
- INDEFREY, P., HELLWIG, F., HERZOG, H., SEITZ, R. J., & HAGOORT, P. (2004). Neural responses to the production and comprehension of syntax in identical utterances. *Brain & Language*, **89**, 312-319.
- JONIDES, J., SMITH, E. E., MARSHUETZ, C., KOEPPPE, R. A., & REUTER-LORENZ, P. A. (1998). Inhibition in verbal working memory revealed by brain activation. *Proceedings of the National Academy of Sciences*, **95**, 8410-8413.
- JOSHI, A. K., & SCHABES, Y. (1997). Tree-adjointing grammars. In G. Rozenberg & A. Salomaa (Eds.), *Handbook of formal languages* (pp. 69-124). Berlin: Springer-Verlag.
- JUST, M. A., & CARPENTER, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, **99**, 122-149.
- JUST, M. A., CARPENTER, P. A., & KELLER, T. A. (1996). The capacity theory of comprehension: New frontiers of evidence and arguments. *Psychological Review*, **103**, 773-780.
- KAAN, E., & SWAAB, T. Y. (2002). The brain circuitry of syntactic comprehension. *Trends in Cognitive Sciences*, **6**, 350-356.
- KERNS, J. G., COHEN, J. D., MACDONALD, A. W., III, CHO, R. Y., STENGER, V. A., & CARTER, C. S. (2004). Anterior cingulate, conflict monitoring, and adjustments in control. *Science*, **303**, 1023-1026.
- KIM, A. E., SRINIVAS, B., & TRUESWELL, J. C. (2002). The convergence of lexicalist perspectives in psycholinguistics and computational linguistics. In P. Merlo & S. Stevenson (Eds.), *The lexical basis of sentence processing: Formal, computational, and experimental perspectives* (pp. 109-135). Philadelphia: Benjamins.
- LEWIS, R. (1996). Interference in short-term memory: The magical number two (or three) in sentence processing. *Journal of Psycholinguistic Research*, **25**, 93-115.
- LUCIANA, M., & NELSON, C. A. (1998). The functional emergence of prefrontally guided working memory systems in four- to eight-year-old children. *Neuropsychologia*, **36**, 273-293.
- LURIA, A. R. (1973). *The working brain: An introduction to neuropsychology*. New York: Basic Books.
- MACDONALD, A. W., III, COHEN, J. D., STENGER, V. A., & CARTER, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, **288**, 1835-1838.
- MACDONALD, M. C. (1994). Probabilistic constraints and syntactic ambiguity resolution. *Language & Cognitive Processes*, **9**, 157-201.
- MACDONALD, M. C., & CHRISTIANSEN, M. (2002). Reassessing working memory: Comment on Just and Carpenter (1992) and Waters and Caplan (1996). *Psychological Review*, **109**, 35-54.
- MACDONALD, M. C., PEARLMUTTER, N. J., & SEIDENBERG, M. S. (1994). The lexical nature of syntactic ambiguity resolution. *Psychological Review*, **101**, 676-703.
- MACLEOD, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, **109**, 163-203.
- MASON, R. A., JUST, M. A., KELLER, T. A., & CARPENTER, P. A. (2003). Ambiguity in the brain: What brain imaging reveals about the processing of syntactically ambiguous sentences. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **29**, 1319-1338.
- MAZZOCCO, M. M. M. (1997). Children's interpretations of homonyms: A developmental study. *Journal of Child Language*, **24**, 441-467.
- McELREE, B. M., & DOSHER, B. A. (1989). Serial position and set size in short-term memory: The time course of recognition. *Journal of Experimental Psychology: General*, **118**, 346-373.
- MCRAE, K., SPIVEY-KNOWLTON, M. J., & TANENHAUS, M. K. (1998). Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory & Language*, **38**, 283-312.
- MENDELSON, A. (2002). *Individual differences in ambiguity resolution: Working memory and inhibition*. Unpublished doctoral dissertation, Northeastern University.
- METZLER, C. (2001). Effects of left frontal lesions on the selection of context-appropriate meanings. *Neuropsychology*, **15**, 315-328.
- MILHAM, M. P., BANICH, M. T., & BARAD, V. (2003). Competition for priority in processing increases prefrontal cortex's involvement in top-down control: An event-related fMRI study of the Stroop task. *Cognitive Brain Research*, **17**, 212-222.
- MILHAM, M. P., BANICH, M. T., WEBB, A., BARAD, V., COHEN, N. J., WSZALEK, T., & KRAMER, A. F. (2001). The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. *Cognitive Brain Research*, **12**, 467-473.
- MILLER, E. K., & COHEN, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, **24**, 167-202.
- MIYAKE, A., JUST, M. A., & CARPENTER, P. A. (1994). Working memory constraints on the resolution of lexical ambiguity: Maintaining multiple interpretations in neutral contexts. *Journal of Memory & Language*, **33**, 175-202.
- MONSELL, S. (1978). Recency, immediate recognition memory, and reaction time. *Cognitive Psychology*, **10**, 465-501.
- NATHANIEL-JAMES, D. A., & FRITH, C. D. (2002). The role of the dorsolateral prefrontal cortex: Evidence from the effects of contextual constraint in a sentence completion task. *NeuroImage*, **16**, 1094-1102.
- NELSON, J. K., REUTER-LORENZ, P. A., SYLVESTER, C. C., JONIDES, J., & SMITH, E. E. (2003). Dissociable neural mechanisms underlying response-based and familiarity-based conflict in working memory. *Proceedings of the National Academy of Sciences*, **100**, 11171-11175.
- NEWPORT, E. (1990). Maturation constraints on language learning. *Cognitive Science*, **14**, 11-28.
- NOOPENEY, U., & PRICE, C. J. (2004). An fMRI study of syntactic adaptation. *Journal of Cognitive Neuroscience*, **16**, 702-713.
- NOVICK, J. M., JANUARY, D., TRUESWELL, J. C., & THOMPSON-SCHILL, S. L. (2004). *Prefrontal cortex and the role of selectional processes in language comprehension: Frogs, napkins, and Broca's area*. Poster presented at the 17th Annual CUNY Conference on Human Sentence Processing, Baltimore.
- NOVICK, J. M., KIM, A., & TRUESWELL, J. C. (2003). Studying the grammatical aspects of word recognition: Lexical priming, parsing, and syntactic ambiguity resolution. *Journal of Psycholinguistic Research*, **32**, 57-75.
- NOVICK, J. M., TRUESWELL, J. C., JANUARY, D., & THOMPSON-SCHILL, S. L. (2004). *The role of conflict resolution in parsing: Measuring individual differences in syntactic ambiguity resolution and executive control*. Paper presented at the 10th Annual Conference on Architectures and Mechanisms in Language Processing, Aix-en-Provence, France.
- PEARSON, D. A., & LANE, D. M. (1991). Auditory attention switching: A developmental study. *Journal of Experimental Child Psychology*, **51**, 320-334.
- PETERSON, S. E., FOX, P. T., POSNER, M. I., MINTUN, M., & RAICHEL, M. E. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature*, **331**, 985-989.
- PRIBRAM, K. H. (1997). The work in working memory: Implications for development. In N. A. Krasnegor & G. R. Lyon (Eds.), *Development of the prefrontal cortex: Evolution, neurobiology, and behavior* (pp. 359-378). Baltimore: Brookes.
- RAYNER, K., CARLSON, M., & FRAZIER, L. (1983). The interaction of syntax and semantics during sentence processing: Eye movements in the analysis of semantically biased sentences. *Journal of Verbal Learning & Verbal Behavior*, **22**, 358-374.
- RIDDERINKHOF, K. R., ULLSPERGER, M., CRONE, E. A., & NIEUWENHUIS, S. (2004). The role of the medial frontal cortex in cognitive control. *Science*, **306**, 443-446.
- ROBERTS, R., & GIBSON, E. (2002). Individual differences in sentence memory. *Journal of Psycholinguistic Research*, **31**, 573-598.
- ROBINSON, G., BLAIR, J., & CIPOLOTTI, L. (1998). Dynamic aphasia: An inability to select between competing verbal responses? *Brain*, **121**, 77-89.
- SNEDEKER, J., & TRUESWELL, J. C. (2004). The developing constraints on parsing decisions: The role of lexical-biases and referential scenes

- in child and adult sentence processing. *Cognitive Psychology*, **49**, 238-299.
- SPIVEY, M., TANENHAUS, M., EBERHARD, K., & SEDIVY, J. (2002). Eye movements and spoken language comprehension: Effects of visual context on syntactic ambiguity resolution. *Cognitive Psychology*, **45**, 447-481.
- SPIVEY-KNOWLTON, M., & SEDIVY, J. C. (1995). Resolving attachment ambiguities with multiple constraints. *Cognition*, **55**, 227-267.
- STROOP, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, **18**, 643-662.
- TANENHAUS, M. K., SPIVEY-KNOWLTON, M. J., EBERHARD, K. M., & SEDIVY, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, **268**, 1632-1634.
- TARABAN, R., & MCCLELLAND, J. L. (1988). Constituent attachment and thematic role assignment in sentence processing: Influences of content-based expectations. *Journal of Memory & Language*, **27**, 597-632.
- THOMPSON-SCHILL, S. L., BEDNY, M., & GOLDBERG, R. F. (2005). The frontal lobes and the regulation of mental activity. *Current Opinion in Neurobiology*, **15**, 219-224.
- THOMPSON-SCHILL, S. L., D'ESPOSITO, M., AGUIRRE, G. K., & FARAH, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences*, **94**, 14792-14797.
- THOMPSON-SCHILL, S. L., JONIDES, J., MARSHUETZ, C., SMITH, E. E., D'ESPOSITO, M., KAN, I. P., KNIGHT, R. T., & SWICK, D. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive, Affective, & Behavioral Neuroscience*, **2**, 109-120.
- THOMPSON-SCHILL, S. L., SWICK, D., FARAH, M. J., D'ESPOSITO, M., KAN, I. P., & KNIGHT, R. T. (1998). Verb generation in patients with focal frontal lesions: A neuropsychological test of neuroimaging findings. *Proceedings of the National Academy of Sciences*, **95**, 15855-15860.
- TRUESWELL, J. [C.], & GLEITMAN, L. R. (2004). Children's eye movements during listening: Developmental evidence for a constraint-based theory of sentence processing. In J. M. Henderson & F. Ferreira (Eds.), *The interface of language, vision, and action: Eye-movements and the visual world* (pp. 319-346). New York: Taylor & Francis, Psychology Press.
- TRUESWELL, J. C., PAPAFRAGOU, A., & CHOI, Y. (in press). Syntactic and referential processes: What develops? In E. Gibson & N. Pearlmuter (Eds.), *The processing and acquisition of reference*. Cambridge, MA: MIT Press.
- TRUESWELL, J. C., SEKERINA, I., HILL, N. M., & LOGRIP, M. L. (1999). The kindergarten-path effect: Studying on-line sentence processing in young children. *Cognition*, **73**, 89-134.
- TRUESWELL, J. C., & TANENHAUS, M. K. (1994). Toward a lexicalist framework of constraint-based syntactic ambiguity resolution. In C. J. Clifton, L. Frazier, & K. Rayner (Eds.), *Perspectives on sentence processing* (pp. 155-179). Hillsdale, NJ: Erlbaum.
- TRUESWELL, J. C., TANENHAUS, M. K., & GARNSEY, S. M. (1994). Semantic influences on parsing: Use of thematic role information in syntactic ambiguity resolution. *Journal of Memory & Language*, **33**, 285-318.
- VITKOVITCH, M., & HUMPHREYS, G. W. (1991). Perseverant responding in speeded naming of pictures: It's in the links. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **17**, 664-680.
- WARBURTON, E., WISE, R. J. S., PRICE, C. J., WELLER, C., HADAR, U., RAMSAY, S., & FRACKOWIAK, R. S. (1996). Noun and verb retrieval by normal subjects: Studies with PET. *Brain*, **119**, 159-179.
- WATERS, G. S., & CAPLAN, D. (1996). The capacity theory of sentence comprehension: Critique of Just and Carpenter (1992). *Psychological Review*, **103**, 761-772.
- WILSHIRE, C. E., & MCCARTHY, R. A. (2002). Evidence for a context-sensitive word retrieval disorder in a case of nonfluent aphasia. *Cognitive Neuropsychology*, **19**, 165-185.
- ZHANG, J. X., FENG, C. M., FOX, P. T., GAO, J. H., & TAN, L. H. (2004). Is left inferior frontal gyrus a general mechanism for selection? *NeuroImage*, **23**, 596-603.
- ZURIF, E. B., CARAMAZZA, A., & MYERSON, R. (1972). Grammatical judgments of agrammatic aphasics. *Neuropsychologia*, **10**, 405-417.

NOTES

1. Of these tasks, the letter recognition task is the most syntactically complex, requiring participants to hold in memory an unordered list of four items (e.g., four letters). Thus, at best, the task may require the use of a simple flat structure to represent the list.

2. Our contention here is that sentence comprehension is a *prime example* of a behavior that requires the coordination of multiple representational subsystems. A detailed enough theory of this process—and its necessary representational subsystems—should allow us to predict when conflict resolution is expected to arise and, hence, when the LIFG is expected to be increasingly engaged. We sketch such a theory in the Role of the LIFG in Sentence Processing section, which predicts that the need for control occurs under the rare occasions in which multiple evidential sources initially point toward an analysis that ultimately turns out to be incorrect.

3. The existence of agrammatics (i.e., patients who show specific deficits in grammatical knowledge) supports the claim that syntactic subsystems exist and can be neurally localized, but the evidence to date does not support the further claim that Broca's area is the neural substrate for this subsystem (see Hagoort, 2003, and Hagoort, Wassenaar, & Brown, 2003, for a similar discussion).

4. Although the data to date support this claim about LIFG, a more parsimonious account of the data may be that this region supports more general conflict resolution functions that are often triggered by the high demands imposed by linguistic stimuli (Thompson-Schill, Bedny, & Goldberg, 2005).

5. Crucially, when the optional complementizer *that* is inserted into the sentence (. . . *accepted that the . . .*), removing the temporary ambiguity and forcing an SC interpretation, eye movement patterns and reading times indicate comparatively little processing difficulty (see Ferreira & Henderson, 1990; Trueswell, Tanenhaus, & Garnsey, 1994).

6. To the best of our knowledge, only one other fMRI study in the literature has examined syntactic ambiguity resolution (Noppeney & Price, 2004). Their study of ambiguity, however, was embedded in a complex design whose ultimate goal was to measure syntactic priming. Moreover, the findings from only some of the conditions were reported—for example, garden-path and non-garden-path sentences appeared to be collapsed in all analyses. As a result, the specific comparisons reported in that article are difficult to relate to our own theory.

7. We reiterate here that we are not referring to patients with Broca's aphasia, which is a syndrome diagnosed on the basis of a cluster of behavioral impairments rather than of a lesion site. We also remind the reader that focal lesions to Broca's area do not result in Broca's aphasia and that patients with Broca's aphasia do not necessarily have lesions that involve Broca's area (see Dronkers et al., 2004).

8. Mendelsohn (2002) used the term "inhibition" abilities rather than "control" abilities. We believe that inhibition is likely to be a component of overriding regularized processes, but for ease of exposition we continue to use the term "control."