Logic, Language and the Brain

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Abstract

What is the role of language in human cognition? Within the domain of deductive reasoning, the issue has been the focus of numerous investigations without the emergence of a consensus view. Here we consider some of the reasons why neuroimaging studies of deductive reasoning have generated mixed results. We then review recent evidence suggesting that the role of language in deductive reasoning is confined to an initial stage in which verbally presented information is encoded as non-verbal representations. These representations are then manipulated by mental operations that are not based on the neural mechanisms of natural language.

Keywords: deductive reasoning, natural language, functional neuroimaging

1. Introduction

The relation between language and other kinds of higher cognition is a central question in Cognitive Science (Gleitman and Papafragou, 2005; Levinson, 2003; Spelke and Tsivkin, 2001). The issue has been confronted in a variety of domains, including mental arithmetic (Dehaene et al., 1999; Varley et al., 2005), music (Brown et al., 2006), communicative competence (Willems and Varley, 2010) and theory of mind (Varley and Siegal, 2000). The present paper reviews the issue with respect to deductive reasoning.

For the purposes of the following review, our comparison of language and deductive inference will rely on the thesis that the principal elements

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of human linguistic capacity are embodied in structures proximal to the left sylvian fissure (including inferior frontal and posterior temporal cortices; c.f., Monti et al., 2009). Indeed, while many aspects of communicative competence have been shown to rely on areas that fall outside of this region (Moro et al., 2001; Rodd et al., 2005; Ullman, 2001), most neuroimaging studies aimed at localizing the central components of language comprehension consistently recruit perisylvian areas. These studies include evaluating semantic equivalence of distinct sentences (Dapretto and Bookheimer, 1999), morphological processing (Sahin et al., 2006), detecting semantic roles (Bornkessel et al., 2005), transforming sentence syntax (Ben-Shachar et al., 2003), and comprehending discourse (Kuperberg et al., 2006; Virtue et al., 2006). (See Willems and Varley, 2010 for a recent review comparing the neural substrate of communicative versus linguistic capabilities.)

1.1. Background

Deductive reasoning is the attempt to draw secure conclusions from prior beliefs, observations and suppositions. It has been the focus of vigorous investigation within philosophy and psychology (e.g., Beall and van Fraassen, 2003; Johnson-Laird and Byrne, 1991; Osherson, 1975). While deduction is often regarded as a central feature of human intelligence (Rips, 1994), some forms of deduction (notably, transitive inference) have been reported in non-human primates (e.g., Gillian, 1981), rats (e.g., Davis, 1992; Roberts and Phelps, 1994), birds (e.g., Steirn et al., 1995; Bond et al., 2003) and fish (Grosenick et al., 2007). In this report our focus will be deductive reasoning in humans and its neural implementation in the adult brain.

Evidence regarding the neural organization of deductive reasoning initially relied on studies of neurological patients with focal brain lesions. This literature suggests the involvement of lateral frontal and pre-frontal regions in deduction, along with various temporal and parietal areas (Grossman and Haberman, 1987; Langdon and Warrington, 2000; Stuss and Alexander, 2000). Clinical studies, however, have been hindered by task heterogeneity, lack of precise localization, and limited replicability of findings (Shuren and Grafman, 2002). Only more recently have lesion studies allowed more precise localization and definition of the contribution of different brain regions to human reasoning (e.g., Goel et al., 2004, 2007; Reverberi et al., 2009b). Since the advent of non-invasive neuroimaging techniques (e.g., positron emission tomography, PET, and functional magnetic resonance imaging, fMRI) the study of deduction in the healthy brain has illuminated a range of issues. Deductive reasoning has been compared to probabilistic inference (Goel et al., 1997; Goel and Dolan, 2004; Parsons and Osherson, 2001) and grammatical transformations (Monti et al., 2009), as well as to mathematical operations (Kroger et al., 2008). Diverse logical domains have also been investigated. Different studies have focussed on deontic and social reasoning (Canessa et al., 2005; Fiddick et al., 2005), propositional arguments (Monti et al., 2007; Reverberi et al., 2007) along with categorical (Osherson et al., 1998; Parsons and Osherson, 2001; Rodriguez-Moreno and Hirsch, 2009) and relational syllogisms (Knauff et al., 2002, 2003; Fangmeier et al., 2006). Other work has investigated the impact of familiar and unfamiliar information (Goel et al., 2000; Goel and Dolan, 2001; Noveck et al., 2004), prior beliefs (Goel and Dolan, 2003a), and emotional content (Goel and Dolan, 2003b) on the neural implementation of deductive inference. Further investigations have addressed the role in deduction of visual imagery (Knauff et al., 2002, 2003), spatial representation of propositions (Prado et al., 2010b), and alternative modalities of stimulus presentation (Fangmeier and Knauff, 2009; Rodriguez-Moreno and Hirsch, 2009). But despite many important findings, a decade of neuroimaging has not produced agreement on which neural areas support deductive reasoning. Consensus is also lacking about the role in deduction of regions traditionally associated with linguistic competence. Indeed, until recently, no two studies have exhibited similar patterns of activation across the brain. As an example, the study of relational syllogisms has been reported to recruit inferior frontal linguistic regions in the absence of any parietal activation in one study (Goel et al., 1998), and bilateral parietal regions in the absence of any inferior frontal linguistic activation in a different one (Goel and Dolan, 2001). Overall, as pointed out in a recent review, all studies "implicate some combination of occipital, parietal, temporal and frontal lobes, basal ganglia, and cerebellar regions in logical reasoning, and several implicate all of these regions" (Goel, 2007, p. 438).

1.2. Sources of variance: Modes of reasoning and experimental design

The observed variance across studies may have several sources (c.f., Monti et al., 2007; Reverberi et al., 2007; Rodriguez-Moreno and Hirsch, 2009). For one thing, deductive reasoning should be regarded as a collection of processes and representations that are differentially triggered by specific features of a reasoning problem (e.g., different logical domains such as quantifiers versus sentential connectives). Deduction also interacts with other cognitive systems (e.g., for resolving cognitive conflict when premises are known to be false). We review these issues in the remainder of the present section.

1.2.1. Deductive domains

Deductive reasoning is often treated as a unitary process governing secure inference across different types of logic. It is possible, however, that propositional problems (based on connectives like "if ... then ...", "and", "not", Monti et al., 2007; Noveck et al., 2004), recruit different mechanisms than those serving categorical syllogisms (based on quantifiers such as "all", "none", "some", Goel et al., 1998, 2000; Rodriguez-Moreno and Hirsch, 2009). Yet other mechanisms may be involved in relational syllogisms (involving relational terms like "...is taller than ...", Goel and Dolan, 2001; Knauff et al., 2003; Prado et al., 2010b). To illustrate the impact of these distinctions on brain activations, relational problems may recruit posterior parietal regions (e.g., Goel and Dolan, 2001; Knauff et al., 2003) that are known to underlie the kind of spatial representation evoked by transitive relations like "taller than" (Kosslyn et al., 1995; Prado et al., 2010b). Such regions would not be expected for connectives, which seem devoid of spatial interpretation. Differences between deductive domains have been noted previously (Goel, 2007), but mostly on the basis of cross-study comparisons. Only recently has the issue been addressed directly by comparing the neural basis of alternative domains within the same participants executing the same experimental task (Prado et al., 2010a; Reverberi et al., 2010).

1.2.2. Stimuli

Another source of variability across studies stems from the specific features of the stimuli employed. For example, some experiments employ "content free" stimuli (e.g., Knauff et al., 2003; Monti et al., 2007; Reverberi et al., 2007), allowing deduction to transpire free of interaction with background knowledge (e.g., "If there is a circle then there is a triangle", Prado et al., 2010a). Other experiments employ statements that may confirm or contradict stored information (e.g., "All poodles are pets" in Goel et al., 2000; see also Goel et al., 1997; Osherson et al., 1998; Parsons and Osherson, 2001). Compared to content free problems, premises or conclusions that contradict knowledge might recruit mechanisms for conflict reduction, suppressing immediate rejection of the statements at issue; statements that are confirmed by prior knowledge might recruit the obverse mechanism. The impact of prior knowledge in reasoning has thus been the focus of several studies (Goel et al., 2000; Goel and Dolan, 2003a; Reverberi et al., 2009a).

Another stimulus-effect on deduction might arise from the use of "simple/effortless" versus "complex/effortful" inferences (as in Goel et al., 2000; Reverberi et al., 2007 on the one hand, and Monti et al., 2007; Rodriguez-Moreno and Hirsch, 2009, on the other). Finally, a last stimulus difference relates to the use of different kinds of invalid arguments. Specifically, we may distinguish invalid arguments whose conclusions may or may not be true given the premises from invalid arguments whose conclusions are contradicted by the premises. Some investigators (Goel et al., 2009, 2007) affirm that the first kind of invalidity, rather than the second, promotes the recruitment of right-lateralized pre-frontal regions in deductive reasoning.

1.2.3. Baseline Task

A critical source of variability between studies relates to differences in the baseline tasks used to isolate deductive reasoning. In standard (blood oxygenation level dependent) neuroimaging, the absolute metabolic response to a task of interest is difficult to interpret. More informative is the difference between the task of interest and a "baseline" condition. In high-level activities such as reasoning, the choice of baseline task is fundamental to filtering-out ancillary non-deductive processes that participate in the task of interest. Such ancillary tasks include, for example, reading the stimuli and distinguishing premises from conclusion. The issue is illustrated by Knauff et al. (2003) who used rest intervals as a baseline for analyzing reasoning about three-term series. The nonspecific nature of rest makes it difficult to assess whether the left posterior temporal activations elicited by the inferential task in this study reflect reading of the (verbal) stimuli or an active involvement of linguistic resources in deductive inference.

Beyond rest, some baseline tasks may require only superficial processing of stimuli. The baseline appearing in Goel et al. (1997), and Goel et al. (1998), for example, required subjects to determine how many of the three sentences in a given argument had people as subject. The (minimal) amount of linguistic processing required by this baseline is likely to be less than reading the same sentences in view of inferential reasoning; for this reason, the observed activations in linguistic regions are difficult to interpret. In Goel et al. (2000), the baseline task resembled deduction trials but included a conclusion unrelated to the premises. To illustrate, compare the following deductive trials, each with two premises and one conclusion:

INFERENCE:

All poodles are pets.
All pets have names.
[Therefore] All poodles have names.

BASELINE:

All poodles are pets.
All pets have names.
[Therefore] No napkins are white.

The obvious presence of extraneous materials in the baseline is sufficient to mark its invalidity, without need of processing the full argument. Moreover, the slow sequential presentation of each premise and conclusion (at 3 seconds intervals), allows deduction to take place upon display of the second premise prior to seeing the conclusion (as acknowledged by Goel et al., 2000, p. 506). Since participants could not know, in advance of seeing the conclusion, whether a given trial was a reasoning or a baseline trial, this design may thus subtract essential elements of deductive reasoning from deduction trials, while not adequately filtering reading activations (c.f., Monti et al., 2007). It is not surprising, then, that this contrast highlighted linguistic activations (in left inferior frontal gyrus, BA 44) for *both* "contentful" and "content-less" inferences.

A different approach was adopted in Osherson et al. (1998), and Parsons and Osherson (2001), where the very same materials were presented to participants for inductive and deductive inference (along with a semantic task). The two forms of reasoning are both likely to elicit thorough reading of the materials, thus canceling-out activations due to pure reading and understanding. However, the restriction of comparisons to invalid trials (supporting both deductive and probabilistic reasoning) may have affected the generalizability of the results (c.f. Goel, 2007). At the opposite end of the spectrum, some baseline tasks may hide important elements of deduction. In Monti et al. (2007), for example, complex deductive inferences were contrasted with simpler (but linguistically matched) ones. Compared to the complex inferences, the simple inferences may be expected to require similar amounts of ancillary processes, particularly reading and encoding of the stimuli. But on the other hand, it is possible that some essential element of deduction is not sensitive to load, and may thus be obscured by the deductive-load design (Kroger et al., 2008). While this is indeed a possibility, it appears to be contradicted by the fact that the same pattern of results was later replicated using a non-deductive baseline (Monti et al., 2009, §7, appendix). In an interesting evaluation of the claim that logic is based on syntactic processing, Kroger et al. (2008) compare complex inferences to simpler ones, and logic inferences to arithmetic processing. In this design, the arithmetic task can be expected to appropriately filter out working memory and reading related activity from the logic trials. However, arithmetic operations are syntactic in nature, and may thus obscure any trace of syntactic processing from the deductive trials.

2. The neural basis of deductive reasoning: A working hypothesis

In a recent series of fMRI experiments we have aimed at re-evaluating (a) the neural basis of (propositional) deductive inference; and (b) the role of linguistic resources in deduction (Monti et al., 2007, 2009). In particular, we have focused on deductive inference-making in the absence of factors such as familiarity of materials (Goel et al., 2000), presence of emotionally salient contents (Goel and Dolan, 2003b), use of heuristic strategies (Reverberi et al., 2009a), and conflict between the truth value of the conclusion statement and the validity of the inference (Goel and Dolan, 2003a). The impact of all these factors on reasoning has been the focus of the pioneering work by Goel and colleagues (see Goel, 2007, for an overview); here, they are set aside. As we will describe below, across different sets of stimuli, semantic content of arguments, and baseline tasks our results replicate with remarkable precision. In addition, these findings have been independently replicated and extended to other modes of logic (i.e., categorical syllogisms) employing a different set of stimuli, baseline task, experimental procedure and modality of presentation (i.e., visual versus auditory; Rodriguez-Moreno and Hirsch, 2009). Finally, recent brain lesion data also lends support to our findings (Reverberi et al., 2009b). We now review the experimental methods that were employed in the experiments, and then sketch a working hypothesis about the neural substrate of deductive reasoning.

2.1. Method

In the two experiments described in Monti et al. (2007), we addressed points (a) and (b) above by contrasting the neural activations elicited by complex inferences with those elicited by simpler, but linguistically matched, inferences (see Table 1). From a cognitive perspective, complex and simple deductions are expected to recruit the same kind of mental operations, but in different number, repetition or intensity. If linguistic structures are involved in the inferential process, complex deductions should recruit them significantly more than simpler ones. On the other hand, if the role of language is confined to initial encoding of stimuli, simple inferences can be expected to require similar levels of reading compared to their complex counterparts. This expectation is reinforced by the fact that our simple and complex inferences were matched for linguistic complexity (compare the statements comprising the simple and complex arguments in Table 1). Therefore, should any language-related activation be apparent, it can not be considered to reflect differences in initial reading or comprehension (for a discussion on linguistic versus logical complexity, see Noveck et al., 2004).

Please insert Table 1 about here.

The experiment described in Monti et al. (2009) addressed the role of linguistic resources in deduction using a different technique than the load method of Monti et al. (2007). Specifically, Monti et al. (2009) compared logic inferences based on sentential connectives (i.e., "if … then …", "and", "or", "not") to linguistic inferences based on the syntax and semantics of ditransitive verbs (e.g., "give", "say", "take"). In this design, logic and linguistic arguments were each compared to a matched baseline in which, the very same sentences evaluated for inferential validity were also evaluated for grammatical well-formedness. The presence of "catch trials" containing grammatical anomalies assured full reading of stimuli in baseline trials. (See Table 2 for sample stimuli.) If logical inference is based on mechanisms of natural language that go beyond mere reading for meaning then the comparison of each type of inference to its matched baseline should uncover common activations in regions known to underlie linguistic processing. (For the latter regions, see Ben-Shachar et al., 2003, 2004; Bookheimer, 2002; Bornkessel et al., 2005; Friederici et al., 2006; Grodzinsky and Friederici, 2006; Kuperberg et al., 2006; Virtue et al., 2006.)

Please insert Table 2 about here.

2.2. Activations for sentential logic

As can be seen in Figure 1, across all three experiments the deductive contrast involving sentential connectives uncovered a highly consistent set of areas (shown in green).

Please insert Figure 1 about here.

The convergence is especially noteworthy in light of the methodological differences between the experiments. These include:

i. baseline task (deductive versus non-deductive)

ii. logical form (e.g., 3-statement versus 2-statement deductions)

iii. lexical content of arguments (e.g., features of an imaginary face, features of an imaginary geometric object versus nonsense words, and the tokens 'X,Y,Z' — see Tables 1 and 2)

iv. analysis methodology (namely, use of a "matching windows" analysis in Monti et al., 2007 versus analysis of the full inference-making period in Monti et al., 2009).

What unites the three studies is principally their common use of sentential connectives. A similar pattern of activation was recently reported by Rodriguez-Moreno and Hirsch (2009). The latter investigation, moreover, differed in experimental design from our own. In particular, the deductions in Rodriguez-Moreno and Hirsch (2009) were based on categorical statements rather than sentential connectives. Also, the lexical content of their statements described familiar scenarios about which participants were likely to have prior beliefs (e.g., "Every politician likes wildlife.", "Some grown-ups make snowmen."), unlike the belief-neutral stimuli used in our experiments. In addition, deductive activations were isolated using a novel non-deductive working memory baseline. Finally, the pattern of activations they described was uncovered independently of the modality of stimuli presentation (i.e., visual versus auditory).

2.3. Language and logic

Across different presentation modalities, lexical contents of arguments, and experimental procedures, none of the four experiments discussed above reported activations in regions typically associated with language processing. On the one hand, greater deductive complexity is not associated with greater activity in linguistic regions. (But greater reading load, in the absence of any deduction, is associated with increased response of posterior temporal linguistic regions; see Monti et al., 2007, online supporting materials, §2). On the other hand, the (equal) level of activation of linguistic resources prompted by simple and complex deductions is no greater than that prompted by reading for grammatical evaluation (Monti et al., 2009) or later recall (Rodriguez-Moreno and Hirsch, 2009). In addition, when directly compared, the neural mechanisms underlying logic inferences dissociate from the neural mechanisms underlying linguistic operations, which have been well documented in the past (Ben-Shachar et al., 2003, 2004; Bornkessel et al., 2005; Friederici et al., 2006). The first set of results hinges on the finding that language regions are not engaged by deductive reasoning, nor are they modulated by deductive complexity. While these findings are negative, they are difficult to reconcile with the suggestion that language plays a central role in deduction (Polk and Newell, 1995) and that the latter is derived from the former (Quine, 1970). Furthermore, our second set of results consist of a double dissociation, observed at the full brain and ROI levels. This dissociation is consistent with the idea that logic arguments are unpacked into non-linguistic representations and then submitted to a mentally represented deductive calculus that is independent of language (Parsons and Osherson, 2001). In the context of deductive reasoning, linguistic resources may be required to decode verbally presented arguments, but beyond this stage, the inferential processes is carried out in extra-linguistic regions. In contrast, when inferences rely on aspects of language processing (Kuperberg et al., 2006; Virtue et al., 2006; Monti et al., 2009), linguistic resources appear to be sufficient for inference-making.

2.4. The neural basis of deductive inference

With respect to the network of regions recruited by logic inference, we hypothesize that it divides into three sets of functionally distinct areas, as follows:

Core regions. We propose that "core" regions encompass areas in left rostrolateral (BA 10) and medial prefrontal (BA 8) cortices. They underlie construction of the derivational path that allows successive logical operations to convert premises into conclusion (in the case of validity). Indeed, rostrolateral cortex has been often reported for tasks requiring integration of information (Christoff et al., 2001; De Pisapia and Braver, 2008; Kroger et al., 2002) and embedded operations (van den Heuvel et al., 2003; Ramnani and Owen, 2004). Similarly, the mesial superior frontal cortex has been associated with the selection and coordination of multiple subgoals (Koechlin et al., 2000) as well as tasks requiring multiple rules to transform an initial state into a final one (Volz et al., 2005). A recent patient study provides convergent evidence on the core role in deduction of medial prefrontal cortex (Reverberi et al., 2009b). Patients with left lateral, medial, and right lateral prefrontal lesions were tested on deductive reasoning. Left prefrontal lesions impaired the ability to assess the validity of inferences in proportion to working memory deficits; in particular, patients with spared working memory performed similarly to healthy volunteers. Memory-impaired patients, however, retained the ability to judge the relative complexity of deductions, signaling a spared appreciation for the logical structure of the inferences. In contrast, lesions in medial prefrontal cortex impaired *both* the ability to assess the validity of inferences (even in the presence of spared working memory) and to judge their complexity. The authors interpret these findings as demonstrating the importance of medial prefrontal cortex for "identify[ing] and represent[ing] the overall structure of the proof necessary to solve a deductive problem" (Reverberi et al., 2009b, p. 1113). As this discussion highlights, these two prefrontal regions cannot be thought of as exclusive to deductive inference. Rather, we believe they reflect processes that lie at the heart of deduction, but that may well characterize other (non-deductive) aspects of human cognition.

Content-Independent Support Areas. The remaining prefrontal and parietal regions consistently activated across studies (i.e., left BA 6, 7, 8, 9, 40, 47 and BA 6 medial) are proposed to be implicated in representing the structure of arguments, reflecting a general cognitive support role (e.g., working memory). Previous literature has implicated these regions in functions including allocation of spatial attention (Tanaka et al., 2005), manipulation of information in working memory (Hanakawa et al., 2002), maintaining serial structure of motor sequences (Jubault et al., 2007), maintaining compound rules across delays (Bunge et al., 2003), representing numerical and spatial information (Pinel et al., 2001), and serial updating of verbal information (Tanaka et al., 2005). (See Monti et al., 2007, for a complete discussion.)

Content-Dependent Support Areas. The last component of our proposed network is comprised of content specific support regions, which we hypothesize to be implicated in buffering information about the lexical content of logic arguments. To illustrate, consider the logical form underlying the top two arguments in Table 1 (where "$\rightarrow$", "$\vee$" and "$\sim$" stand for "if ... then ...", "or" and "not", respectively). The form in question is:

$$(p \vee q) \rightarrow \sim r$$
$$r$$
$$\sim q$$

The variables "p, q, r" can be replaced with any sentences without affecting the validity of the argument. In Monti et al. (2007) we tested the notion of content-dependent support regions by comparing brain activation in response to the same logical forms when different lexical contents replaced the variables (see Table 1). When the sentences concerned a hypothetical house additional activations were detected in the parahippocampal gyrus, whereas when they concerned a hypothetical face additional activations were detected in the inferior temporal cortex. These localizations are consistent with what is known about the neural representation of faces and houses. The neural localization of such additional activations is proposed to vary according to the specific lexical contents in play.

3. Alternative hypotheses

In contrast to the language-independent view of deductive reasoning sketched above, at least two other hypotheses have been defended. According to one, the role of linguistic regions in deduction depends on whether the inferences concern familiar or unfamiliar materials (Goel and Dolan, 2001; Goel, 2007). According to the other hypothesis, the substrate of language embodies deductive operations for all stimulus material (Prado et al., 2010a; Reverberi et al., 2007, 2010). We examine these ideas in turn.

3.1. Material-dependent networks for deductive reasoning

Goel et al. (2000) was the first to observe that the neural basis of deductive reasoning is affected by the semantic contents of an argument. More specifically, the presence of materials that are familiar and conceptually coherent with the reasoner's knowledge was proposed to engage a language based fronto-temporal "heuristic" system. Conversely, inferences with unfamiliar, nonconceptual or incoherent materials was proposed to engage a "formal/universal" bilateral parietal system (Goel, 2007). The data in support of this idea, however, ar open to question. First, left inferior frontal linguistic regions (particularly, BA 44) are consistently activated by both "familiar" and "unfamiliar" arguments (c.f., Goel et al., 2000, Table 2, p. 508; see also Goel and Dolan, 2003a,b, 2004). It is therefore difficult to qualify just one of these networks as "linguistic." Second, posterior temporal activation (likewise conceived as language-related) is highly inconsistent across investigations. In Goel and Dolan (2003a), for example, the only temporal activation reported falls in the left anterior pole, a region more than 6 centimeters away from the (classical) linguistic focus found in Goel et al. (2000). In Goel and Dolan (2004) contentful syllogisms including statements likely to elicit the reasoner's prior beliefs (e.g., "All animals with 32 teeth are cats.") do not appear to recruit temporal cortex at all, while activating left inferior frontal linguistic regions (BA 44) together with posterior parietal cortex (BA 7), a pattern similar to that expected for inferences over non-familiar contents. A similar lack of temporal activation, accompanied by activations in posterior parietal cortex, is also seen in other investigations with contentful syllogisms that are likely to engage prior beliefs (Rodriguez-Moreno and Hirsch, 2009). Overall, it is possible that content plays some role in selecting the neural underpinnings of reasoning; however, familiarity, coherence of materials, and prior beliefs do not seem to be critical to the involvement of language areas in deduction.

3.2. Deduction as a language based process

The idea that deductive inference is language based (for all argument content) has been advanced several times (e.g., Goel et al., 1997, 1998; Goel and Dolan, 2004), and has received recent support (Reverberi et al., 2007, 2010). Employing a novel experimental design, Reverberi et al. (2007) found that the integration of premises for simple propositional inference elicits left lateralized frontal (BA 6, 44) and parietal (BA 40) activations. Importantly, the frontal cluster falls within regions typically associated with language processing, supporting the idea that linguistic operations may be fundamental to deductive inference. This result was later extended to categorical syllogisms, which were found to recruit the same sections of the inferio frontal gyrus along with the same focus within left BA 6 (Reverberi et al., 2010). Unlike Reverberi et al. (2007), however, parietal regions were only found to be active for categorical syllogisms Overall, inference in the two studies elicited significant activation of the left inferior frontal gyrus (in BA 44 and BA 45).

Using the same experimental procedure employed by Reverberi and colleagues, Prado et al. (2010a) compared the neural basis of inferences based on propositional connectives to inferences based o relational terms. The authors reported two main findings. First, inferences based on connectives recruited different cortical areas than inferences based on transitive relations. This finding may be compared to the results of Reverberi et al. (2010) on transitive syllogisms, furthering the notion that deduction should be conceived as a heterogeneous collection of cognitive processes sensitive to the specific logical vocabulary on which the inferences rely (e.g., sentential connectives, quantifiers or relational terms, Monti et al., 2009). Second, Prado et al. (2010a) interpret activation in left inferior frontal gyrus, specific to connectives, as supporting the view that linguistic/syntactic processes contribute to some domains of deduction. The latter conclusion, however, may be unwarranted. Indeed, the activation described falls in a (medial) region of the inferior frontal gyrus, very different from the (lateral) sections typically implicated in syntactic tasks (e.g. Bornkessel et al., 2005; Dapretto and Bookheimer, 1999, c.f., Grodzinsky and Friederici, 2006; Kaan and Swaab, 2002; Price, 2000). The medial region reported by Prado et al. (2010a), often referred to as the "deep frontal operculum" (Anwander et al., 2007), has been proposed to serve articulatory planning (Price, 2000). When this function is controlled for, there is little if any involvement of this area in syntactic tasks (Rogalsky and Hickok, in press). Similarly, while the deep frontal operculum has been implicated in retrieval and maintenance of (spatial and verbal) abstract rules (Bunge et al., 2003), this is believed to be in connection with subvocal rehearsing (Bunge, 2004).Overall, despite the use of a common experimental procedure, it is difficult to interpret the findings of Prado et al. (2010a) as supporting the language-based view of deduction proposed by Reverberi and colleagues.

4. Logic, language and the brain: Where do we stand?

When considering the involvement of linguistic resources in deductive reasoning, it is important to distinguish two potential roles. It is evident that linguistic resources must be recruited for initial reading and encoding of verbally presented stimuli. More controversial is whether language plays a part in the subsequent inferential process. Evaluating this latter point has proven difficult, for at least two reasons. First, recruitment of a given neural region may be triggered by particular features of an inference, such as the specific logical vocabulary on which it relies (e.g., propositional connectives, quantifiers, relational terms). Second, it is often difficult to disentangle activations reflecting the deductive process from activations reflecting accompanying ancillary processes, such as reading.

A recent series of results (Monti et al., 2007, 2009; Rodriguez-Moreno and

Hirsch, 2009) nonetheless suggests that language areas are not involved in the deductive process, a finding consistent with several previous reports (Canessa et al., 2005; Fangmeier et al., 2006; Goel and Dolan, 2001; Knauff et al., 2002; Noveck et al., 2004; Parsons and Osherson, 2001; Prado and Noveck, 2007). We interpret these findings as implying that the role of language is confined to initial encoding of verbal statements into mental representations suitable for the inferential calculus. The representations themselves, as well as the deductive operations, are not linguistic in nature. A different view, stressing the centrality of language regions to deduction, has been recently advocated by Reverberi and colleagues (Reverberi et al., 2007, 2010). How can the two sets of findings be reconciled? One way of reducing the discrepancy is suggested by the results of Prado et al. (2010a). In this study, the experimental design departed from that used in Reverberi et al. (2010) in only one important feature, namely, the complexity of the logic arguments. Prado and colleagues make exclusive use of the *modus tollens* logic form, a structure more complex than *modus ponens*, aa well as the conjunction and disjunction problems used by Reverberi and coworkers (c.f., Garnham and Oakhill, 1994, p. 78). It is possible that effortless inferences may be entirely supported by linguistic comprehension, while effortful deductions require a qualitatively different set of processes, not supported by the neural mechanisms of language. This possibility is consistent with the finding that BA 44/45 is implicated in spontaneous (non-deductive) causal inference-making during text comprehension (Kuperberg et al., 2006; Virtue et al., 2006). On the other hand, the foregoing hypothesis seems inconsistent with the impaired performance, on elementary deductions, of prefrontal patients with preserved language skills (Reverberi et al., 2009b). The latter finding seems to indicate that linguistic resources are not sufficient for deductive inference.

A second factor that may help explain the discrepant recruitment of language resources across experiments, is the use of different means for eliciting deductive reasoning (c.f., Reverberi et al., 2007). It is possible that the crucial feature engaging linguistic mechanisms is the necessity to generate a deductive conclusion (as in Reverberi et al., 2007, 2010), as compared to evaluating a conclusion that is provided (as in Monti et al., 2007, 2009; Rodriguez-Moreno and Hirsch, 2009). This distinction might explain why prefrontal patients with intact linguistic resources could not correctly assess the validity of provided inferences (Reverberi et al., 2009b). But this proposal cannot explain the failure to activate, in the generation task employed in Prado et al. (2010a), the sections of inferior frontal gyrus reported in

Reverberi et al. (2007) and Reverberi et al. (2010).

Several studies have reported remarkable dissociations between cognitive and linguistic abilities (e.g., in theory of mind and arithmetic; see Varley and Siegal, 2000; Varley et al., 2005). Yet the role of language in human thought remains a controversial issue (Gleitman and Papafragou, 2005; Levinson, 2003). With respect to deductive reasoning in a mature healthy brain, we propose the role of language to be confined to initial encoding of verbally presented materials; neither the mental representations formed as a result of the initial encoding nor the deductive operations themselves appear to be supported by the neural mechanisms of natural language. Whether these latter mechanisms contribute to the development of deductive competence remains to be investigated.

5. References

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Table Captions

Table 1: Sample stimulus material from Monti et al. (2007). Experiments I and II used the same 4 simple/complex pairs of logic forms (half valid, half invalid). In Experiment I, each logic form was shown twice to participants, once using contents describing an imaginary geometric figure, and once using nonsense words. In Experiment II, the same eight logic forms were also shown twice, once using contents describing the features of an imaginary face, and once using contents describing an imaginary house.

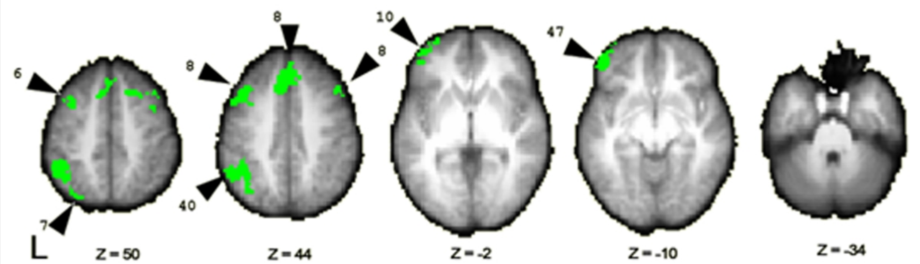
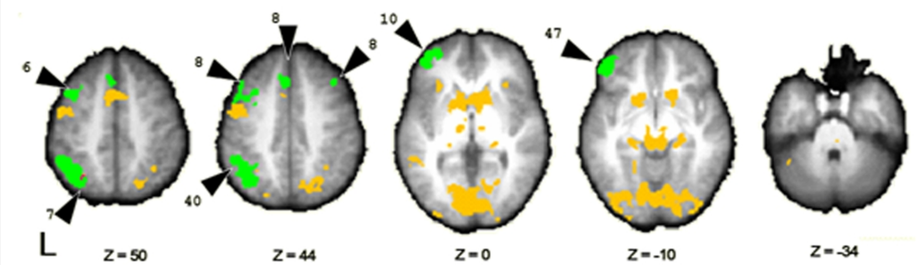
Table 2: Sample stimulus material from Monti et al. (2009). The same arguments were shown for the inference and the baseline tasks. Sample catch trials (only shown in the baseline condition) are also shown. ('*' indicates a non-grammatical sentence; the * was not shown in the experimental procedure).

Figure Captions

Figure 1: Regions activated by logical inference across three studies. The left column reports the main features of the experimental design for each study; the right column depicts the activations for the logic contrast (in green) using the same slice prescription. The top two rows report the results from experiments I and II in Monti et al. (2007), respectively, while the third row describes the results obtained in Monti et al. (2009).

	Experiment I	
Trial Type	“Concrete” content	“Abstract” content
Complex	If the block is large or yellow then it is not round. The block is round. The block is not yellow.	If there is sug or rop then it is no tuk. There is tuk. There is no rop.
Simple (baseline)	If the block is green or square then it is not small. The block is square. The block is not small.	If there is rek or sem then it is no gez. There is sem. There is no gez.
	Experiment II	
Trial Type	“Face” content	“House” content
Complex	If he has a frown then he does not have open eyes. He has open eyes. He does not have a frown.	If it has a pitched roof then it has no chimney. It has a chimney. It does not have a pitched roof.
Simple (i.e. baseline)	If he has a long nose then he does not have a smile. He has a long nose. He does not have a smile.	If it has a front stoop then it has no garage. It has a garage. It does not have front stoop.

Trial Type	"Logic" arguments	"Linguistic" arguments
Inference	If either not Z or not X then Y. If not Y then both Z and X.	It was X that was given to Z by Y. What Y gave Z was X.
Grammar (no anomaly)	If either not Y or not X then Z. If not Z then both Y and X.	It was Z that was given to Y by X. What X gave Y was Z.
Grammar (anomaly)	*If either not X not or Z then Y. If not Y then both Z and X.	It was X that was given to Y by Z. *What Z gave X was to Y.

Contrast: Logic Inference vs. Logic Grammar **Contents:** Single letters (i.e. X,Y,Z) **N = 15**	
Contrast: Complex Logic Inference vs. Simple Logic Inference **Contents:** Features of imaginary faces and houses **N = 12**	
Contrast: Complex Logic Inference vs. Simple Logic Inference **Contents:** Features of imaginary shapes and pseudo-words **N = 10**