Functional neuroanatomy of deductive inference: A language-independent distributed network

Martin M. Monti,[a] Daniel N. Osherson,[a] Michael J. Martinez,[b] and Lawrence M. Parsons[b,*]

[a]Department of Psychology, Princeton University, Princeton, NJ 08540, USA
[b]Department of Psychology, The University of Sheffield, Western Bank, Sheffield, S10 2TP, UK

Studies of brain areas supporting deductive reasoning show inconsistent results, possibly because of the variety of tasks and baselines used. In two event-related functional magnetic imaging studies we employed a cognitive load paradigm to isolate the neural correlates of deductive reasoning and address the role (if any) of language in deduction. Healthy participants evaluated the logical status of arguments varying in deductive complexity but matched in linguistic complexity. Arguments also varied in lexical content, involving blocks and pseudo-words in Experiment I and faces and houses in Experiment II. For each experiment, subtraction of simple from complex arguments (collapsing across contents) revealed a network of activations disjoint from regions traditionally associated with linguistic processing and also disjoint from regions recruited by mere reading. We speculate that this network is divided into "core" and "support" regions. The latter include left frontal (BA 6, 47) and parietal (BA 7, 40) cortices, which maintain the formal structure of arguments. Core regions, in the left rostral (BA 10p) and bilateral medial (BA 8) prefrontal cortex, perform deductive operations. Finally, restricting the complex−simple subtraction to each lexical content uncovered additional activations which may reflect the binding of logical variables to lexical items.
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Deductive reasoning is the attempt to reach secure conclusion from prior beliefs, observations or suppositions. It is a distinguishing feature of human intellect and has been the focus of vigorous investigation within psychology and philosophy (Johnson-Laird and Byrne, 1991; Rips, 1994; Hacking, 2001).

Evidence about the neural basis of deduction once depended solely on studies of neurological patients with focal lesions.

Viewed broadly, this literature has generally implicated the lateral frontal and prefrontal cortices in deductive processing, perhaps with temporal or parietal involvement (e.g., Grossman and Haberman, 1987; Langdon and Warrington, 2000; Stuss and Alexander, 2000). Lesion studies, however, may be limited by insufficient precision about brain areas, the heterogeneity of tasks used, and even unreplicability of findings (Shuren and Grafman, 2002).

In the last decade, the neuropsychological literature has been complemented by neuroimaging studies of deduction in healthy individuals (e.g., Goel et al., 1997; Osherson et al., 1998; Parsons and Osherson, 2001; Knauff et al., 2003; Noveck et al., 2004). Despite the growing literature, however, there is little agreement about (a) the neural correlates of deductive reasoning and (b) the role of language in deductive inference. Regarding (a), some reports have characterized deduction as predominantly left hemispheric, variously recruiting regions in inferior frontal (Goel et al., 1997), fronto-temporal (Goel et al., 1998), occipito-fronto-parietal (Goel and Dolan, 2001), and occipito-fronto-temporo-parietal (Goel and Dolan, 2004) cortices. Others studies recorded mostly right hemispheric activations, in temporal and frontal regions (Osherson et al., 1998; Parsons and Osherson, 2001). Bilateral activations have also been reported, in fronto-temporo-parietal areas (Knauff et al., 2003). It has also been proposed that reasoning selectively engages left hemispheric linguistic regions for inferences involving content about which subjects have prior beliefs and bilateral parietal cortex for inferences lacking this feature (Goel and Dolan, 2003). With respect to (b), deduction has been variously described as primarily based on linguistic substrate (Goel et al., 1997, 1998; Goel and Dolan, 2004), entirely independent of it (Parsons and Osherson, 2001; Knauff et al., 2003), as well as selectively recruiting linguistic structures for inferences involving prior beliefs (Goel et al., 2000; Goel and Dolan, 2003).

One source of disagreement across previous studies might be the use of different kinds of deductive tasks. Thus, Osherson et al. (1998) and Parsons and Osherson (2001) use invalid arguments drawn from quantified and sentential logic, respectively. Goel et al. (1997), on the other hand, employed both valid and invalid quantified and sentential arguments, whereas Goel et al. (2000)

* Corresponding author. Fax: +44 114 276 6515.
 E-mail addresses: mmonti@princeton.edu (M.M. Monti),
osherson@princeton.edu (D.N. Osherson), L.Parsons@sheffield.ac.uk
(L.M. Parsons).

relied exclusively on quantified logic. Furthermore, Goel and Dolan (2001) and Knauff et al. (2003) make use of three-term series problems, which some logicians have been reluctant to qualify as part of logic (Quine, 1970, p. 77). Such differences in stimuli may elicit different reasoning strategies, and hence recruit different neural substrates. Additionally, some studies rely on stimuli that engage prior beliefs (e.g., Goel et al., 1997; Osherson et al., 1998; Parsons and Osherson, 2001; Knauff et al., 2003), whereas others make use of content-neutral materials (e.g., Knauff et al., 2003; Fangmeier et al., 2006).

Another factor clouding interpretation of previous studies is the possible use of heuristics instead of deduction. Thus, Reverberi et al. (submitted for publication) provide experimental evidence that time pressure and quantified stimuli may have prompted participants in Goel et al. (2000) to rely on the well-known "atmosphere" heuristic (Woodworth and Sells, 1935; Chapman and Chapman, 1959; Gilhooly et al., 1999) rather than logic.

Different baseline tasks can also lead to divergent claims about the neural regions responsible for deduction as well as discrepant estimates of the role of linguistic processing in reasoning. In Goel et al. (2000), for example, baseline trials were identical to deduction ones except for the presence of a conclusion entirely unrelated to the premises. The baseline argument could thus be recognized as invalid just by spotting the extraneous content of the conclusion (signaled by its novel first noun); the entire argument need not be fully processed. Moreover, the sequential presentation of premises and conclusion for each argument (at 3 s intervals) allowed deduction to take place upon display of the second premise, prior to receiving the conclusion (subjects did not know in advance of the conclusion whether a trial was baseline versus deduction). This baseline task may thus subtract essential elements of deductive reasoning from deduction trials, while not filtering adequately reading activations. Similar considerations apply to Goel and Dolan (2001), Goel and Dolan (2003) and Goel

and Dolan (2004). Other studies, addressing different questions, make no attempt to distinguish reasoning from mere reading inasmuch as rest intervals are used as a general baseline (e.g., Knauff et al., 2003, which compares visualizable versus non-visualizable inferences).

In the present paper we report two event-related fMRI experiments addressing the neural basis of deductive reasoning and the role of language. For this purpose, we directly compare complex inferences to simpler but linguistically equivalent ones. From a cognitive perspective, complex and simple inferences are expected to recruit the same kind of mental operations but in different number, repetition, or intensity. See Fig. 1 for an example of linguistically matched simple and complex arguments.

This "cognitive load" design has been successfully exploited in other areas of cognitive neuroscience (e.g., Jonides et al., 1997; Stromswold et al., 1996; van den Heuvel et al., 2003; Rodd et al., 2005). Our use of linguistically matched arguments with distinct deductive complexity allows us to avoid comparing deduction to a different cognitive task while controlling for aspects of linguistic processing due to simple reading. (See Friston et al., 1996 for a discussion of the "pure insertion" problem.) In overview, our fMRI design (i) compares brain activity on items with different levels of behaviorally validated logical "load" but identical syntactic complexity (thus eliminating the need for a non-deductive baseline task), (ii) compares deduction with formally identical structures across different kinds of semantic content, and (iii) allows the reading stage of each trial to be analyzed separately from deduction (which is time-locked to subjects' button press). Our fMRI design is event-related (but without overlapping hemodynamic responses). Finally, prompted by the lack of successful replication in the existing literature, we repeated Experiment I with new subjects and stimuli of the same logical form but different semantic content (Experiment II).

Experiment I			
Argument Status	Formal Arguments	Block Instantiation	Abstract Instantiation
Valid, Simple	$(P \lor Q) \Rightarrow \neg R$ P $\therefore \neg R$	If the block is either round or large then it is not blue. The block is round. $\therefore$ The block is not blue.	If there is either sug or rop then there is no tuk. There is sug. $\therefore$ There is no tuk.
Valid, Complex	$(P \lor Q) \Rightarrow \neg R$ R $\therefore \neg P$	If the block is either red or square then it is not large. The block is large. $\therefore$ The block is not red.	If there is either bep or tuk then there is no gez. There is gez. $\therefore$ There is no bep.

Experiment II			
Argument Status	Formal Arguments	Face Instantiation	House Instantiation
Valid, Simple	$(P \lor Q) \Rightarrow \neg R$ P $\therefore \neg R$	If he has either open eyes or a smile then he doesn't have a long nose. He has open eyes. $\therefore$ He doesn't have a long nose.	If it has either a front stoop or a bay window then it has no garage. It has a front stoop. $\therefore$ It has no garage.
Valid, Complex	$(P \lor Q) \Rightarrow \neg R$ R $\therefore \neg P$	If he has either a small nose or closed eyes then he doesn't have a frown. He has a frown. $\therefore$ He doesn't have a small nose.	If it has either brick siding or a chimney then it has no tree in front. It has a tree in front. $\therefore$ It has no brick siding.

Fig. 1. Sample pair of linguistically matched arguments (simple and complex) for each of the four lexical contents appearing in Experiments I and II. See Section 3 in Supplementary Materials for a complete list of stimuli.

Materials and methods

Subjects

Ten (all male) and twelve (6 female) right-handed Princeton University undergraduates with no formal training in logic took part in Experiment I and II, respectively. All subjects were native English speakers with no history of neurological disorders and signed informed consent in accordance with the Declaration of Helsinki and the Princeton University Institutional Review Panel prior to participation. In a prescreening session, correct assessment of 28 out of 32 arguments was required for potential participants to qualify for the remainder of the study. The 32 arguments were novel instantiations of the formal structures used to generate arguments in the two experiments.

Stimuli

To create stimuli for both experiments, eight formal arguments from Sentential Logic were chosen; each consisted of two premises and one conclusion (for a complete list see Section 3 in Supplementary Materials). The eight arguments were organized into four pairs, two pairs consisting of valid arguments, the other two invalid. Syntax was matched within a given pair in the sense that the same connectives appeared in the same positions, and each argument involved the same variables (p, q, r). Each formal argument generated multiple natural language arguments by substituting different phrases for the variables p, q, and r. The phrases employed four types of lexical content, involving *blocks* and *pseudo-words* (Experiment I), and *faces* and *houses* (Experiment II). Logical connectives were translated standardly ("If … then …", "not", "or", "and", translating $\rightarrow$, $\neg$, $\wedge$, $\vee$, respectively). See Fig. 1 for examples. Crucially, the arguments in a given pair differed in deductive complexity (despite their linguistic parity). Complexity differences within a pair were validated in a separate behavioral study using (a) average response times required to assess validity, (b) subjective complexity rating, and (c) pair-wise complexity comparison. (See Section 1 in Supplementary Materials for a detailed report of methods and results.)

In each of the experiments reported below, participants assessed the validity of 40 arguments. Thirty-two were generated by lexically instantiating each formal argument 4 times. In Experiment I the arguments were instantiated twice using block-features and twice using pseudo-words. Similarly, arguments in Experiment II were twice instantiated with face-features and twice with house-features. The two instantiations of each formal argument within a given domain (e.g., blocks) were made distinct by choosing different lexical items (e.g., "green" versus "blue"). The remaining eight arguments were "fillers," not analyzed, and used only to prevent subjects from detecting the simple–complex pairs.

Experimental design

Each trial displayed a single argument. The trial began by on-screen presentation of the first premise alone for 3 s. The argument was then completed by adding the second premise and conclusion for a further 15 s. A fixation period of 14 s separated trials, with a dot replacing the fixation cross 2 s prior to the following trial. Subjects were instructed to assess the logic status of each argument and respond via key-press. Answers provided beyond the first 2 s of the fixation period were considered failed trials and discarded from analysis (this occurred only 3 times across the two experiments).

Each experiment consisted of eight 2.54 min scans. A scan was composed of five arguments, namely, one valid pair, one invalid pair and one filler. The five arguments of a given scan were presented in random order with the constraint that the filler appears third and no paired arguments occur contiguously. In Experiment I all participants first viewed block and then pseudo-word arguments (in either of two orders). In Experiment II half the participants viewed the faces trials followed by the houses trials, half viewed the reverse order. Upon completion of the eight functional scans structural MRI data were acquired.

fMRI data acquisition

All data were acquired with a 3 T Siemens Allegra. T_2^* sensitive images were acquired with a gradient echo sequence (TR=2.0 s, TE=30 ms, FA=90°, FOV=192×192 mm) in 32 ascending interleaved slices, AC–PC aligned, with a 3 mm³ resolution and a 0.33 distance factor in the Z direction. Structural images were acquired with a standard MP-RAGE sequence in 176 slices with a 1 mm³ isovoxel resolution.

fMRI data analysis

Analysis methods were performed using FSL (FMRIB Software Library, Oxford University). Prior to functional analyses, each individual EPI time-series was motion corrected to the middle time point (or acquired volume) using a 6 parameter, rigid-body method (as implemented in MCFLIRT, Jenkinson et al., 2002). Data were smoothed with a Gaussian kernel of 5 mm FWHM and signal from extraneous non-brain tissue was removed using BET (Brain Extraction Tool; Smith, 2002). Autocorrelation was corrected using a pre-whitening technique (Woolrich et al., 2001). Statistical analyses were performed using general linear modeling methods as implemented in FEAT (fMRI Expert Analysis Tool; Woolrich et al., 2001; Beckmann et al., 2003). Prior to multi-subject analyses, each individual data set was coregistered to the MNI152 standard template brain. Data for each subject were brought into coregistration with the template using 9 and 12 parameter optimization methods (Jenkinson et al., 2002). Group mean statistics for each contrast were generated with a mixed-effects models resulting from the use of within-session variance (i.e., fixed-effects) at the single subject level and between-session variance (i.e., random-effects) at the group level (Friston et al., 2005). Statistical parametric maps were thresholded at a (corrected) cluster significance level of $p<0.001$ (Worsley et al., 1992).

For each scan, three contrasts were performed: complex–simple, invalid–valid, and valid–invalid. All incorrect trials were excluded. To preserve the linguistic balance between simple and complex arguments we also excluded arguments whose matched mate was incorrectly evaluated. Within each pair of matched arguments we equalized the number of volumes analyzed. For the simple argument, we included the second volume through the response volume (i.e., the volume that includes the subject's response). The first volume is excluded because only the first premise appears, so deduction cannot be initiated. For the complex argument we included the same number of volumes but counted back from the response volume. Thus, for each matched pair, the same number of volumes was analyzed for the complex versus

simple argument, namely, the intervals ending with the response volumes of each and extending back at most to the second volume.

In addition to the load analysis, in every trial we contrasted the first volume (during which the subject is reading the first premise) against fixation. Because the first volume preceded deduction, this subtraction provides an (inclusive) estimate of reading-only. We refer henceforth to this analysis as the "reading contrast."

Results

Behavioral results

Participants accurately detected the logic status of arguments in 93.44% and 95.3% of the trials in Experiment I and II, respectively (the worst individual score was 87.5%). Response time data replicated the load effect seen in the experiment validating argument complexity. (See Table 1 for response time data in the behavioral study and the two fMRI experiments.)

Functional brain activations (Experiment I)

The reading contrast for block and pseudo-word stimuli (see Fig. 2, activations in yellow) revealed regions typically observed in reading tasks (Price, 2000; Stowe et al., 2005) and for the maintenance of premise information in spatial inference tasks (e.g., Fangmeier et al., 2006). Thus, there was activity in posterior and inferior areas in superior temporal cortex, as well as putamen, thalamus, visual cortex, parahippocampus, and inferior frontal

cortex. Additional activations in right posterior parietal areas likely support spatial attention (Posner and Deheane, 1994; Colby and Goldberg, 1999) required at task onset (switching from fixation point to spatially arrayed words). Likewise, other activated areas (such as cingulate cortex) may support the initialization of task performance. (See Table 2 for a full list of activations.)

The subtraction of simple arguments from complex (collapsing across block and pseudo-word content) showed no overlap with the reading contrast, except for a small area in the left insula (peaking at −32, 22, −1). See Fig. 2 and Table 3. The dissociation between reading and deduction is confirmed by time course analysis. Fig. 3 plots the activity of the peak voxel in Wernicke's area (as isolated by the reading contrast) versus peak voxels in areas highlighted by the subtraction of simple from complex deductions (as shown in Fig. 2). Deductive activity peaks as reading begins to decline. The same contrast revealed activations in bilateral dorsolateral frontal cortex (middle frontal gyrus, BA 6), medial frontal cortex (BA 8, 6), left lateral rostral prefrontal cortex (BA 10p; 'p' stands for polar, following Ongur et al., 2003), left posterior parietal lobule (BA 40, 7), bilateral inferior frontal cortex (BA 47), insula, and intermediate and lateral aspects of right posterior cerebellum (crus I).

Restricted to block arguments, the complex–simple contrast revealed additional activations in bilateral cingulate cortex (BA 32, 24), left occipital cortex (medial occipital gyrus, BA 18), and right intraparietal sulcus (BA 40). Restricted to pseudo-word content, the complex–simple contrast revealed additional activations in the left hemispheric areas of inferior frontal (BA 47), middle frontal

Table 1
Response time data for the pre-scan behavioral study and Experiments I and II

Status and difficulty	Formal structure	Behavioral experiment ($N=35$)	Experiment I ($N=10$)		Experiment II ($N=12$)	
		RT (SD)	RT (SD) blocks	RT (SD) pseudo-words	RT (SD) faces	RT (SD) houses
Valid, simple	$p \rightarrow \neg q$ p $\neg q$	6.8 (2.89)	8.28 (3.00)	7.81 (2.00)	6.51 (1.27)	6.05 (0.94)
Valid, complex	$p \rightarrow \neg q$ q $\neg p$	14.5 (8.78)	12.32 (4.36)	10.40 (3.79)	10.67 (3.94)	10.40 (3.53)
Valid, simple	$(p \vee q) \rightarrow \neg r$ p r	10.05 (5.16)	8.96 (2.03)	8.25 (1.82)	7.54 (1.82)	8.06 (1.82)
Valid, complex	$(p \vee q) \rightarrow \neg r$ r $\neg q$	18.76 (14.0)	14.54 (4.07)	12.64 (4.63)	11.48 (3.31)	11.53 (3.83)
Invalid, simple	$(p \wedge q) \rightarrow \neg r$ p $\neg r$	8.31 (4.73)	9.12 (2.21)	7.85 (1.77)	8.70 (1.86)	8.01 (1.91)
Invalid, complex	$(p \wedge q) \rightarrow \neg r$ r $\neg p$	13.82 (9.90)	14.16 (3.93)	12.58 (4.17)	10.75 (3.48)	10.70 (2.66)
Invalid, simple	$\neg p \rightarrow (q \vee r)$ $\neg p$ q	8.13 (3.39)	8.73 (1.98)	8.70 (2.49)	7.89 (1.98)	8.72 (2.11)
Invalid, complex	$\neg p \rightarrow (q \vee r)$ $\neg q$ p	19.55 (15.5)	15.02 (4.55)	14.44 (4.58)	12.39 (3.20)	12.27 (3.74)

The first two columns report the logical status, complexity and logical structure of each form. Columns 3–7 report average response times (s) for assessing validity of each logic form in the behavioral evaluation (column 4; see Section 1 in Supplementary Materials for full description of the methods as well as additional data documenting the complexity difference within each pair of arguments), in Experiment I (columns 5–6) and Experiment II (columns 7–8). Complex arguments required longer time to be evaluated, in all three experiments, with respect to their simple counterpart ($p < 0.001$ by correlated t-test).
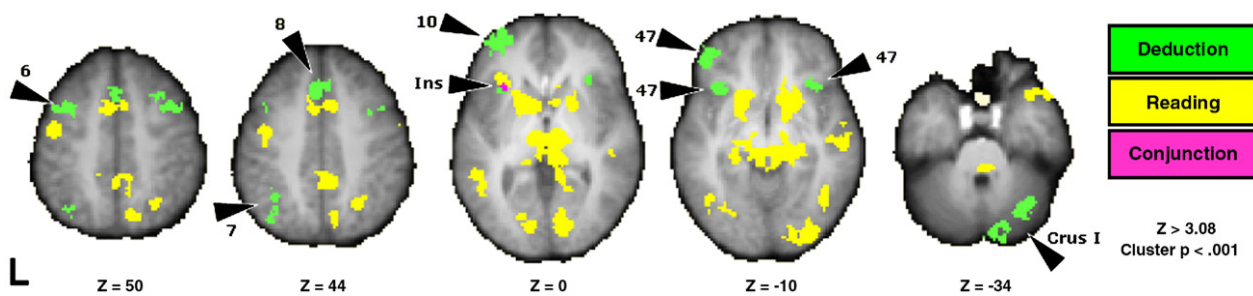
Fig. 2. Group data for Experiment I: areas activated by initial reading (first 2s of all trials) are shown in yellow. Areas specifically isolated by the complex–simple deduction analysis (across logical status and semantic content) are shown in green. The insular region responding to both tasks is shown in pink. Numbers in arrowhead labels indicate Brodmann areas. See Tables 2 and 3.

(BA 47, 11), and medial frontal (BA 8) cortices. See Fig. 4 and Table 4.

We interpret the foregoing results as suggestive of a network for deductive reasoning that is independent of traditional language areas. It is composed of *content-independent* regions that represent and transform formal structures, versus *content-dependent* regions that maintain the identity of logical variables as a function of lexical content. (See the Discussion section for a more complete articulation of this hypothesis.)

The valid–invalid contrasts yielded no activations; neither did invalid–valid when restricted to pseudo-word content. When restricted to block content, the invalid–valid contrast showed activations in dorsolateral frontal cortex (superior and middle frontal gyri, BA 8, 6), lateralized to the right hemisphere.

Functional brain activations (Experiment II)

The functional brain activations observed in Experiment II closely replicated the findings of Experiment I. The reading contrast revealed activations similar to those uncovered by the same contrast in Experiment I (see Fig. 5, activations in yellow). Activated areas include left perisylvian (BA 21/22), left inferior frontal (BA 45, 46), left anterior insula, superior parietal (BA 7), bilateral pre-supplementary motor area (BA 6), bilateral dorsolateral frontal (BA 6), and occipital (BA 17, 18). There were also foci in posterior cerebellum and subcortical structures (midbrain, thalamus, caudate head). (See Table 5 for a full list of activations.)

The subtraction of simple arguments from complex (combining faces and houses instantiations) showed no overlap with the reading contrast, except for a small area in the left posterior parietal (BA 7) (common focus at -30, -64, 54; see Fig. 5). This replicates the pattern seen in Experiment I in which only a small area of overlap was present (in left insula). This same contrast revealed activity in brain areas similar to those uncovered in Experiment I. Specifically, activations across the two experiments were closely matched in regions in the left rostral prefrontal (BA 10p, peaking at -36, 56, 8 and -38, 58, 8, in Experiments I and II, respectively), left medial frontal cortex (BA 8, at -2, 28, 38 and -6, 28, 46), left middle (BA 6, at -46, 10, 50 and -40, 12, 56), and inferior frontal (BA 47 at -32, 20, -8 and -48, 36, -8) cortices, as well as the left superior (BA 7, at -38, -72, 46 and -40, -66, 48) and inferior (BA 40, at -36 -56 42 and -44, -54, 44) parietal lobules. The present subtraction also revealed activity in bilateral middle frontal (BA 9) and superior frontal

(BA 8) gyri, as well as right middle frontal gyrus (BA 46) while failing to detect any activation in right crus I of posterior cerebellum, which was found active in Experiment I. In addition, foci were detected in dorsolateral BA 6 and at the medial edge of BA 47 bilaterally in Experiment I, but were here unilaterally left for BA 6 and left lateral BA 47.

Visual imagery relating to faces and houses has been shown to elicit activation in the fusiform face area (FFA) and in the parahippocampal place area (PPA) (O'Craven and Kanwisher, 2000), respectively. We thus expected to see selective activation in these areas as a function of the lexical content of arguments (referring to faces versus houses) (Table 6).

Indeed, restricting the complex–simple contrast to house trials revealed additional activations in bilateral parahippocampal place area (PPA, BA 35), and occipital cortex (BA 19) along with left inferior parietal lobule (BA 40). This general pattern closely resembles the one found for geometric shapes, in Experiment I (e.g., common activations in occipital and parietal). On the other hand, restricting the contrast to face trials uncovered additional activations (outside the FFA) in the left inferior temporal cortex (BA 20), superior temporal gyrus (BA 22), and right medial orbitofrontal cortex (BA 11). See Fig. 6 and Table 7.

Discussion

Language and logic

Across the four semantic domains (blocks, pseudo-words, faces, and houses), the contrast between complex and simple deductions uncovered regions disjoint from primary language areas. These regions were also disjoint from loci engaged in reading the first premise of arguments, except for minimal overlap in anterior insula, in Experiment I, and in the left posterior parietal cortex (BA 7), in Experiment II. The overlapping clusters are small and fail to replicate across the two experiments. BA 7 may nonetheless reflect temporal overlap in reading and inference (deduction may commence prior to encoding all three statements of an argument).

Our results are thus at variance with the common belief that deduction derives from linguistic manipulation (Quine, 1970; Polk and Newell, 1995; Goel et al., 1997, 1998). They also contradict a popular view according to which language and logic are a unitary phenomenon (Montague, 1974; Partee and Hendriks, 1997). Rather, the data fit an alternative view in which arguments are first unpacked into non-linguistic structural

Table 2
Activations for initial reading of first premise (for all trials) for Experiment I

MNI coordinates			Region label (BA)	Z score
x	y	z		
Frontal				
−6	10	48	Superior frontal gyrus (6)	4.76
−46	−2	30	Precentral gyrus (6)	4.60
−48	−8	54	SMA, Precentral gyrus (6)	4.59
−44	10	26	Inferior frontal gyrus (9)	4.42
6	12	48	Superior frontal gyrus (6)	4.41
−50	16	24	Inferior frontal gyrus (9)	4.36
0	0	66	SMA, Superior frontal gyrus (6)	4.28
42	4	36	Precentral gyrus (9)	4.18
Parietal				
28	−56	42	Superior parietal lobule (7)	4.24
32	−58	46	Superior parietal lobule (7)	3.98
Temporal				
−48	−48	8	Superior temporal gyrus (39)	4.79
60	−6	−16	Inferior temporal gyrus (21)	4.23
−52	−44	−2	Middle temporal gyrus (22)	4.07
36	8	−26	Superior temporal gyrus (38)	4.05
42	22	−36	Superior temporal gyrus (38)	3.93
38	22	−34	Superior temporal gyrus (38)	3.86
Other				
10	−84	2	Lingual gyrus (17)	4.97
6	−30	−6	Parahippocampal gyrus (27)	4.93
−20	8	0	Putamen	4.86
−8	−16	2	Thalamus	4.78
32	−92	−6	Inferior occipital gyrus (18)	4.71
−6	−32	−12	Midbrain	4.60
16	8	−8	Putamen	4.60
−6	−34	−6	Parahippocampal gyrus (30)	4.55
8	−14	10	Thalamus	4.55
20	6	−8	Putamen	4.51
−20	6	−12	Subcallosal gyrus (34)	4.49
20	−88	−6	Inferior occipital gyrus (18)	4.34
−22	−80	24	Precuneus (31)	4.31
−6	−74	24	Cuneus (18)	4.31
−22	16	0	Putamen	4.18
−12	12	−4	Putamen	4.16
−22	16	−10	Subcallosal gyrus (47)	4.08
8	12	−8	Cingulate gyrus (25)	3.86

Coordinates are in millimeters along the left–right (x), anterior–posterior (y), and superior–inferior (z) axes. Throughout, each brain region is assigned an anatomical label and Brodmann area (in parentheses) via initial reference to the Talairach Daemon (Lancaster et al., 2000). In the case of the cerebellum, anatomical labels of Schmahmann et al. (2000) are used. Peak and cluster stereotactic coordinates were used to check all anatomical and BA labels against published literature to ensure these fit with the common consensus. Coordinates were based on activation clusters, such that one maximum was reported per 100 activated voxels.

representations and then submitted to a mentally represented deductive calculus that is independent of language (cf., Parsons and Osherson, 2001).

Neural correlates of deductive reasoning

Our results suggest that deduction is supported by a primarily left hemispheric distributed network primarily in prefrontal, inferior, and superior frontal regions, with contributions from parietal areas. The network appears to be dissociable into content-independent regions (uncovered in load contrasts across all four lexical themes) versus content-dependent regions (selectively activated by different vocabulary). On this hypothesis, the first set of regions represents and manipulates the formal structure of arguments whereas the second maintains the specific identity of logical variables. The previous literature raises the possibility that content-independent regions may be further divided into "core" versus "support" areas. Core regions would carry out deductive operations over formal structures that are extracted and maintained by support regions.

Content-independent core regions

Portions of BA 10p and medial BA 8 may be responsible for the core operations of deduction. Such operations would include transforming logical structure by changing the polarity of variables (e.g., adding negation), displacing variables, and substituting or

Table 3
Activations for complex minus simple deductions (collapsing across valid/invalid and block/pseudo-word trials) for Experiment I

| MNI coordinates			Region label (BA)	Z score
x	y	z		
Frontal				
−36	56	8	Middle frontal gyrus (10p)	4.19
−32	62	0	Middle frontal gyrus (10p)	4.07
−28	58	0	Superior frontal gyrus (10p)	3.98
−2	28	38	Medial frontal gyrus (8)	3.98
32	24	−12	Inferior frontal gyrus (47)	3.95
−40	54	0	Inferior frontal gyrus (10p)	3.93
−32	4	62	Middle frontal gyrus (6)	3.92
−40	50	−6	Middle frontal gyrus (10p)	3.82
−46	10	50	Middle frontal gyrus (6)	3.82
2	30	36	Medial frontal gyrus (6)	3.78
−32	20	−8	Inferior frontal gyrus (47)	3.77
−46	42	−10	Middle frontal gyrus (11)	3.76
−36	6	54	Middle frontal gyrus (6)	3.75
44	12	50	Middle frontal gyrus (6)	3.75
48	10	50	Middle frontal gyrus (6)	3.74
6	28	38	Medial frontal gyrus (8)	3.71
−2	22	46	Medial frontal gyrus (8)	3.68
32	28	−2	Inferior frontal gyrus (47)	3.61
−32	64	12	Middle frontal gyrus (10p)	3.52
−52	40	−12	Inferior frontal gyrus (47)	3.36
−28	60	16	Superior frontal gyrus (10p)	3.19
Parietal				
−36	−56	42	Inferior parietal lobule (40)	3.92
−38	−72	46	Superior parietal lobule (7)	3.44
Other				
−34	20	0	Insula	3.57
Posterior cerebellum				
10	−84	−24	Crus I	3.98
14	−84	−26	Crus I	3.97
32	−66	−36	Crus I	3.96
12	−80	−32	Crus I	3.79
26	−74	−40	Crus I	3.66
38	−60	−34	Crus I	3.65
20	−78	−38	Crus I	3.64
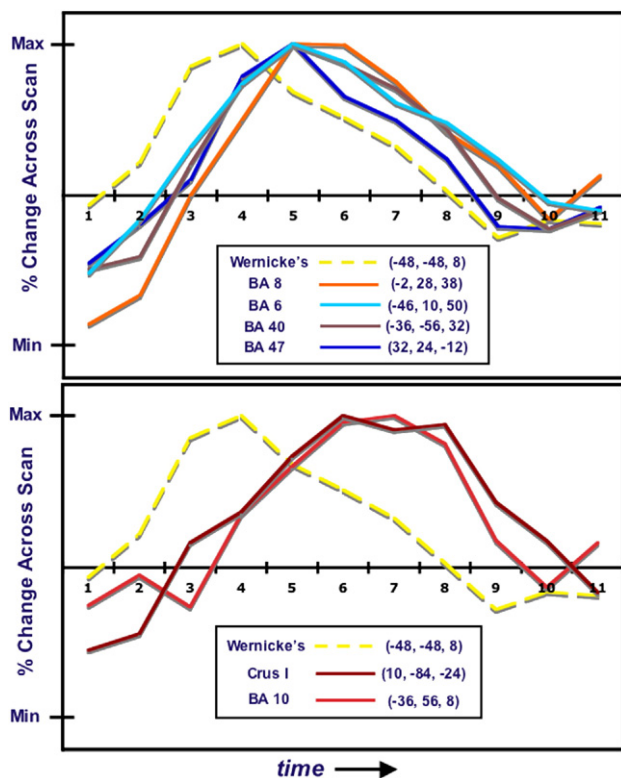
Fig. 3. Time course across all trials for (a) the peak active voxel in Wernicke's area (−48, −48, 8; dashed line), as revealed by the reading contrast, and (b) the peak active voxels for regions revealed in the complex–simple contrast (as shown in Fig. 2 and Table 3). The mean activity per unit time is represented as percent change relative to the maximum and minimum within each scan.

eliminating logical connectives (conjunction, etc.). Indeed, activation of lateral left BA 10p has been observed for inferences that require integrating relational information in visual–spatial patterns (peaking at −34, 50, 9 in Christoff et al., 2001, compared to −36, 56, 8 and −32, 60, 4 in Experiments I and II here). Likewise, this area is active in tasks requiring integration of multiple sub-operations (Koechlin et al., 1999; van den Heuvel et al., 2003; Ramnani and Owen, 2004) and has been associated with high levels of abstraction (Christoff et al., submitted for publication). More generally, lateral BA 10 is recruited by tasks involving greater response times compared to their baseline (Gilbert et al., 2006). See Burgess et al., 2005 for a review of alternative theories of BA 10 activity. Relative to other prefrontal areas, BA 10p exhibits a high dendritic and spine complexity (in terms of length and branching of dendrites, as well as count and density of spines per cell), without an increase in cell bodies (Jacobs et al., 2001; Travis and Jacobs, 2003). In addition, it has marked reciprocal connectivity to other supra-modal areas and receives input exclusively from such areas (Jacobs et al., 2001; Travis and Jacobs, 2003). Thus, this region seems well suited to integrate information and orchestrate multiple operations, essential to reasoning. In addition, during recent hominid evolution, BA 10 has expanded and specialized markedly (e.g., for the foregoing connectivity) (Semendeferi et al., 2001). Moreover, BA 10 (along with BA 8, 9, 46, 47, and rostral 6, with which it has reciprocal projections) matures late in development (Gogtay et al., 2004), with individuals of superior general intelligence showing later maturation in prefrontal cortices by 5 or more years on average (Shaw et al., 2006).

Regions of mesial BA 8 have been implicated in executive control (Posner and Deheane, 1994), and also with selection and coordination of sub-goals (e.g., peaking at −12, 45, 39 in Koechlin et al., 2000, compared to −2, 28, 38 and −6, 28, 46 here; see Fletcher and Henson, 2001 for a review). In addition, mesial BA 8 is recruited for tasks requiring choice among competing rules to transform an initial state into a final state (Volz et al., 2005). It is
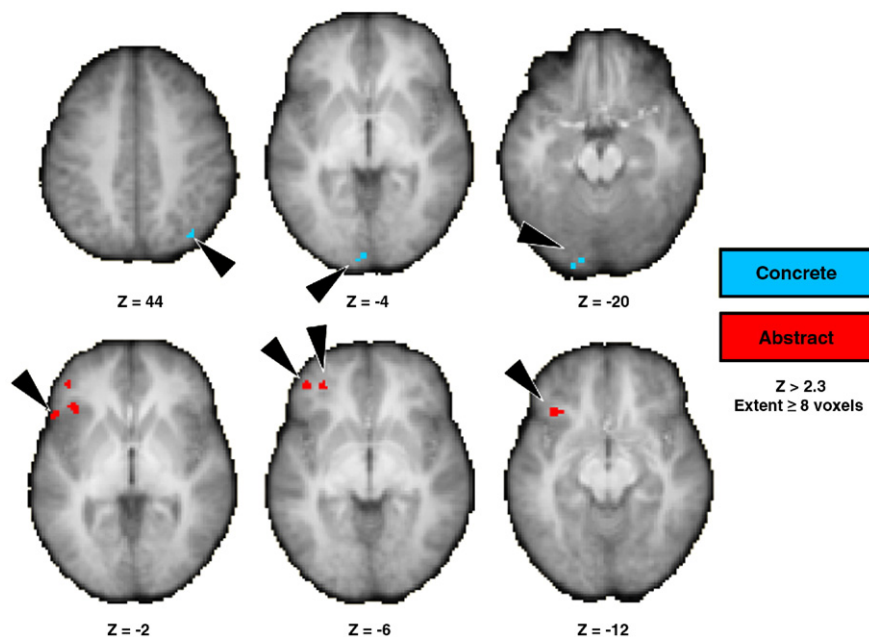

Fig. 4. Areas activated in Experiment I specifically for concrete materials (in blue, upper row) and for abstract materials (in red, lower row) in complex minus simple analyses. See Table 4.

Table 4
Activations for complex minus simple deductions specific to block and pseudo-word content (collapsing across valid–invalid) for Experiment I

MNI coordinates			Region label (BA)	Z score
x	y	z		
Pseudo-word				
−40	28	0	Inferior frontal gyrus (47)	3.38
−44	44	−6	Middle frontal gyrus (47)	3.06
−34	24	−12	Inferior frontal gyrus (47)	2.78
−52	24	−2	Inferior frontal gyrus (47)	2.74
−32	44	−6	Middle frontal gyrus (11)	3.17
−12	40	36	Medial frontal gyrus (8)	3.01
Block				
−10	16	40	Cingulate gyrus (32)	3.23
−12	−96	−20	Medial occipital gyrus (18)	3.19
28	16	32	Cingulate gyrus (24)	3.03
40	−72	44	Inferior parietal lobule (40)	2.56
−4	−98	−4	Lingual gyrus (18)	3.04

thus plausible that this region is instrumental in searching for a deductive path uniting premises to conclusion.

Content-independent support regions

We interpret the remaining content-independent areas (consistently activated across different semantic contents) as support regions. As noted above, such support might consist in extracting and maintaining the logic structure of arguments for manipulation by core areas. Both Experiments I and II revealed content-independent activations in BA 6, 7, 40, and 47. Activation of BA 6 might simply indicate an increase in saccades for complex arguments. However, our peak coordinates in this region are different from those reported in studies localizing frontal eye fields (Lobel et al., 2001; Hanakawa et al., 2002; Rosano et al., 2002). Furthermore, medial BA 6 has been implicated in serially updating positions in a spatial array, and lateral BA 6 in serially updating verbal information (Tanaka et al., 2005). Left BA 6 is also active across numerical, verbal and spatial mental operations in the absence of any motor activity (peaking at −33, −2, 62, in Hanakawa et al., 2002, compared to −32, 4, 62 and −40, 12, 46 in our Experiments I and II). Overall, these comparisons suggest that our dorsolateral BA 6 activations are involved in supporting cognitive manipulation of representations in short-term memory.

Activity in the left BA 47 has been associated with working memory and executive aspects of semantic processing, among

other functions (e.g., Dronkers et al., 2004; Ricci et al., 1999; McDermott et al., 2003; Bookheimer, 2002; Poldrack et al., 1999). In addition, understanding metaphoric sentences, which involves inferences among relations among concepts, activates left BA 47 when contrasted with literal sentences (Rapp et al., 2004). We note, however, that the activations we observed in this area are different from those reported for retrieving and maintaining task-relevant rules (Bunge, 2004; Bunge et al., 2003, 2005).

Activations that we observed in the left inferior parietal lobule (BA 40) are near areas implicated in the representation of spatial information and numerical distance (e.g., with a peak at −40, −44, 36 in Pinel et al., 2001 and −36, −56, 42 and −46, −50, 48 here). Likewise, a recent study reports activity in the intraparietal sulcus across numerical, verbal and spatial mental operations (at about −34, −48, 52, in Hanakawa et al., 2002, compared to −36, −56, 42 and −46, −50, 48 here). Moreover, activity in BA 40 increases in response to demands on working memory (Honey et al., 2000) and has been linked to a variety of spatial cognitive functions (Colby and Goldberg, 1999). Regions of posterior parietal lobule (BA 7) have been related to executive functions such as updating of information, maintenance of order relations, and allocation of spatial attention (Posner and Deheane, 1994; Colby and Goldberg, 1999; Wager and Smith, 2003; Tanaka et al., 2005). Overall, the parietal activation observed in our experiments may thus reflect the representation of spatial relations among argument terms. Selective activations were observed in one study, but not replicated in the other (in BA 6, 8, 9, 46, 47, and cerebellum, in Tables 2 and 4). At present, their role (if any) in deductive reasoning is unclear.

Content-dependent regions

In Experiment I, foci in the left BA 47 appear to provide support for just abstract content. Consistently, Crottaz-Herbette et al. (2004) report engagement of left BA 47 in a verbal working memory task for visually presented stimuli (peaking at −30, 24, −10 in Crottaz-Herbette et al., 2004, and at −34, 24, −12 here). In addition, left BA 47 is activated for retrieval of arbitrary task rules cued by abstract visual/verbal stimuli (e.g., peaking at −36, 33, 0 in Bunge et al., 2003, and at −40, 28, 0 here). This area is also activated for comprehensibility judgments of abstract versus spatial sentences (peaking at −46, 20, 2 and −44, 38, −14 in Wallentin et al., 2005, and −40, 28, 0 and −44, 44, −6 here). Overall, these data implicate left ventrolateral prefrontal cortex in maintenance of verbal information (Fletcher and Henson, 2001). Conversely, when restricted to block arguments, various left occipital and right parietal areas are selectively engaged, likely supporting visual–spatial information about the objects referred to in the arguments
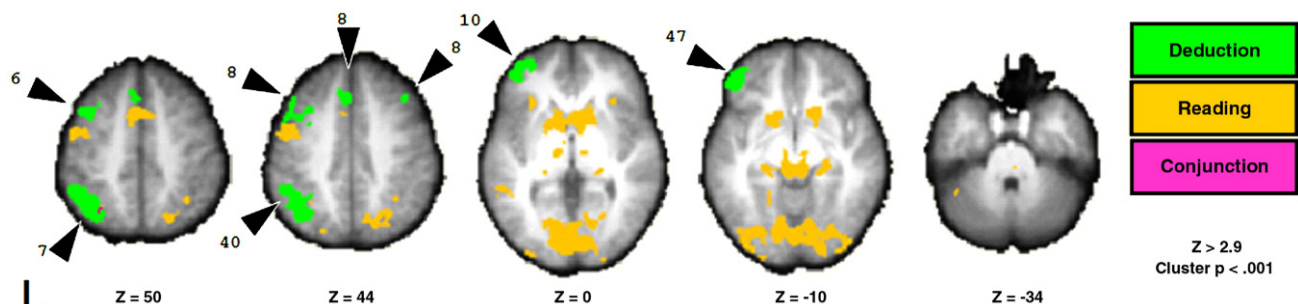

Fig. 5. Group data for Experiment II: areas activated by initial reading (first 2s of all trials) are shown in yellow. Areas specifically isolated by the complex–simple deduction analysis (across logical status and semantic content) are shown in green. The posterior parietal region responding to both tasks is shown in light green. See Tables 5 and 6.

Table 5
Activations for initial reading of first premise (for all trials) for Experiment II

MNI coordinates			Region label (BA)	Z score
x	y	z		
Frontal				
−50	0	42	Middle frontal gyrus (6)	7.32
−8	4	60	Pre-SMA, superior frontal gyrus (6)	6.59
−4	4	58	Pre-SMA, superior frontal gyrus (6)	6.59
−8	12	48	Pre-SMA, medial frontal gyrus (6)	6.01
4	12	50	Pre-SMA, medial frontal gyrus (6)	6.00
−10	22	28	Cingulate gyrus (32)	5.50
−48	16	22	Inferior frontal gyrus (45)	5.46
−50	28	18	Inferior frontal gyrus (46)	5.46
4	−34	26	Cingulate gyrus (23)	5.39
−52	20	12	Inferior frontal gyrus (45)	5.21
−10	20	34	Cingulate gyrus (32)	5.08
−54	24	10	Inferior frontal gyrus (45)	5.02
−42	20	12	Inferior frontal gyrus (44/45)	5.02
30	4	56	Middle frontal gyrus (9)	4.83
34	8	66	Middle frontal gyrus (6)	4.80
34	4	68	Middle frontal gyrus (6)	4.79
Parietal				
−30	−64	54	Superior parietal lobule (7)	8.08
−36	−64	48	Superior parietal lobule (7)	7.95
Temporal				7.79
−58	−46	4	Middle temporal gyrus (21/22)	7.48
−66	−54	6	Middle temporal gyrus (21/22)	7.48
−60	−60	8	Middle temporal gyrus (39)	7.46
−46	−50	0	Middle temporal gyrus (22/39)	5.29
42	−42	−22	Fusiform gyrus (37)	5.57
Occipital				4.99
−10	−82	−4	Lingual gyrus (18)	
−10	−80	2	Cuneus (17)	6.12
−8	−88	0	Lingual gyrus (17)	5.84
−8	−74	10	Cuneus (18)	5.30
10	−88	−6	Lingual gyrus (18)	5.29
−10	−72	−8	Lingual gyrus (18)	4.91
Other				
−6	−32	−8	Midbrain	7.36
−2	−30	−8	Midbrain	7.28
4	−32	−10	Midbrain	7.20
−12	−16	6	Thalamus	6.94
6	14	−2	Caudate head	6.85
14	14	−4	Caudate head	6.71
−30	24	2	Anterior insula (13)	6.58
−4	−36	24	Posterior cingulate (23)	4.81
−6	−40	22	Posterior cingulate	4.70
Posterior cerebellum				
−2	−58	−50	IX (tonsil)	5.77
38	−42	−30	VI	5.54
−22	−38	−52	VIIIA	5.45
34	−46	−26	VI	5.06

(Price, 2000; Scott et al., 2003; Stowe et al., 2005). In Experiment II, house-specific activations were seen in bilateral parahippocampal gyrus, in general agreement with previous reports (e.g., Epstein and Kanwisher, 1998; Wallentin et al., 2005; Epstein et al., 2005). Additional foci in right occipital and left inferior

parietal cortices may likewise be involved in representing the visual–spatial features of houses (Price, 2000; Scott et al., 2003; Stowe et al., 2005; Wallentin et al., 2005). Finally, face-specific activations were found in inferior temporal gyrus (BA 20), but more rostrally than areas that have been implicated in face perception (O'Craven and Kanwisher, 2000). Nonetheless, the appearance of BA 20 for face content and BA 35 for house content adds credence to the hypothesis that specific regions of cortex bind lexical content (e.g., "bay window") to formal propositions (e.g., "*q*").

Reading load

A different interpretation of our results is that activations revealed by the deduction contrasts simply represent increased reading load imposed by complex arguments. The latter arguments may indeed prompt greater reading/re-reading compared to simple arguments. We explored this possibility in an fMRI experiment in which 8 participants (4 female) performed a reading load task on the same materials used in the block trials of Experiment I but in the absence of any logic reasoning. (See Section 2 in Supplementary Materials for a full description of methods and results.) Reading load showed activations similar to the reading contrast in Experiment I, recruiting bilaterally, but predominantly left, peri-sylvian (BA 21, 22, 37) regions, occipital cortex (BA 17, 18), and posterior cerebellum. Left hemispheric activation was detected in the superior and inferior

Table 6
Activations for complex minus simple (collapsed across content and validity) for Experiment II

| MNI coordinates			Region label (BA)	Z score
x	y	z		
Frontal				
−48	24	40	Middle frontal gyrus (9)	4.26
−56	22	32	Middle frontal gyrus (9)	4.26
−40	12	46	Middle frontal gyrus (6)	4.16
−38	12	40	Precentral gyrus (9)	4.11
−48	16	40	Middle frontal gyrus (9)	4.11
−38	16	52	Superior frontal gyrus (8)	4.00
−32	60	4	Middle frontal gyrus (10p)	4.16
−48	36	−8	Inferior frontal gyrus (47)	4.04
−38	58	−4	Middle frontal gyrus (10p)	3.99
−46	50	0	Inferior frontal gyrus (10p)	3.88
−52	44	−8	Middle frontal gyrus (47)	3.47
−46	48	−10	Middle frontal gyrus (11)	3.47
48	28	34	Middle frontal gyrus (9)	3.82
52	20	34	Middle frontal gyrus (9)	3.78
42	28	46	Middle frontal gyrus (8)	3.58
48	24	28	Middle frontal gyrus (46)	3.37
−6	28	46	Medial frontal gyrus (8)	4.31
−2	34	34	Medial frontal gyrus (9)	3.66
−4	38	36	Medial frontal gyrus (9)	3.64
−6	22	56	Superior frontal gyrus (8)	3.50
Parietal				
−34	−66	46	Superior parietal lobule (7)	5.05
−46	−50	48	Inferior parietal lobule (40)	4.75
−50	−46	42	Inferior parietal lobule (40)	4.67
−40	−66	48	Superior parietal lobule (7)	4.51
−44	−54	44	Inferior parietal lobule (40)	4.33
−42	−62	52	Superior parietal lobule (7)	4.28
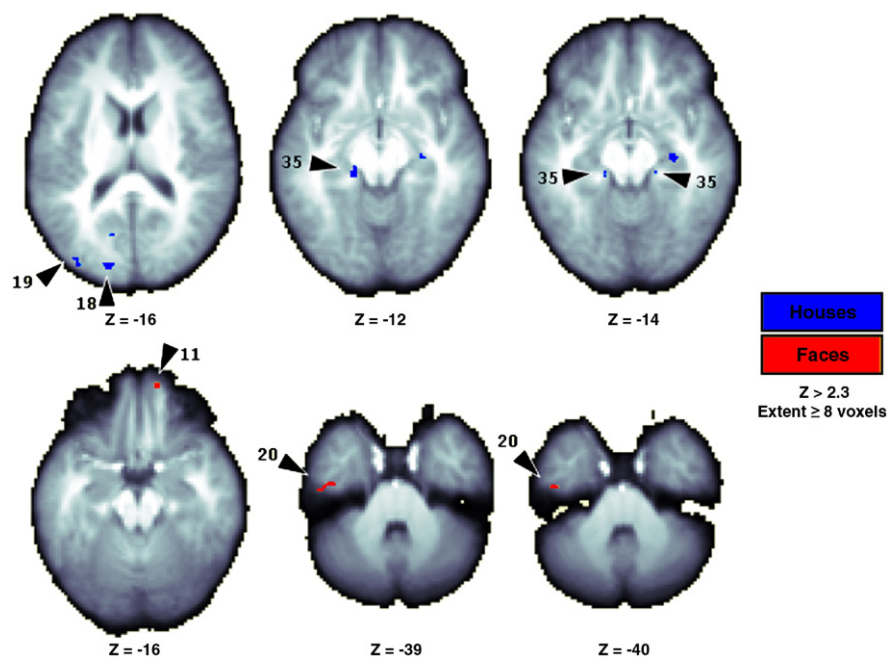
Fig. 6. Areas activated in Experiment II specifically for houses materials (in blue, upper row) and for faces materials (in red, lower row) in complex minus simple analyses. See Table 7.

parietal lobules (BA 7, 40; with one BA 7 focus in the right), bilateral middle frontal gyrus (BA 6), left pre-SMA, and bilateral middle frontal (BA 9). Consistently with the findings in Experiments I and II, the overlap with regions uncovered by the logic load contrast was confined to small regions, in BA 6. The BA 6 activation in the reading load experiment, however, is posterior to that seen in Experiments I and II and may reflect eye movement. This is consistent with the division of BA 6 into a more caudal part implicated in motor behavior (i.e., FEF) and a more rostral part implicated in tasks requiring cognitive manipulation of representations in short memory (see Hanakawa et al., 2002). The reading load contrast revealed no activation in either putative core regions (BA 10p, 8 medial). We interpret these findings as implying that reading load is not a viable interpretation of the activations uncovered by the logic complexity subtraction.

Table 7
Activations for complex minus simple deductions specific to houses and faces content (collapsing across valid–invalid) for Experiment II

MNI coordinates			Region label (BA)	Z score
x	y	z		
Faces				
−44	−16	−40	Inferior temporal gyrus (20)	2.70
−34	−56	16	Superior temporal gyrus (19/22)	2.58
14	56	−20	Superior frontal gyrus (11)	2.46
Houses				
30	−20	−14	Parahippocampal gyrus—hippocampus	3.21
16	−30	−16	Parahippocampal gyrus (35)	3.04
−16	−30	−12	Parahippocampal gyrus (35)	3.02
−62	−34	26	Inferior parietal lobule (40)	3.09
−36	−92	12	Middle occipital gyrus (19)	3.23
−16	−90	16	Cuneus (18)	3.02

Conclusion

Our findings suggest that deduction is supported by a network of cortical loci distinct from areas classically associated with linguistic processing. Moreover, in conjunction with previous findings, the data provide evidence that deductive inference engages distinct content-independent versus content-dependent regions. The former include support areas that maintain the formal structure of arguments and core regions that operate over these structures. Content-dependent regions, on the other hand, buffer information about the identity of logical variables.

Additionally, the present results suggest that core deduction areas, as well as most support areas, are primarily left hemispheric. This conclusion is contrary to our prior findings (Parsons and Osherson, 2001), but consistent with other reports (e.g., Goel et al., 1997; Goel and Dolan, 2004). The results are also inconsistent with the claims of selective activation in bilateral parietal cortex for belief-neutral inferences (Goel et al., 2000; Goel and Dolan, 2003). The discrepancy with earlier studies is likely due to differences in baseline task and in choice of underlying logic (as discussed earlier). It will be important to evaluate these hypotheses using neuropsychological and transcranial magnetic stimulation paradigms.

Finally, we note the relevance of our results to the debate between theories of deductive inference based on *mental models* versus *mental rules* (see Johnson-Laird and Byrne, 1991, and Rips, 1994, respectively). In contrast to predictions of the former theory (Johnson-Laird, 1995), right parietal structures were never activated by deductive load. On the other hand, the rules theory portrays deductive reasoning as requiring a succession of stages that progressively transform the premises into the conclusion. This view seems to be consistent with the engagement of rostro-lateral prefrontal cortex (BA 10p), a region implicated in tasks involving nested goals/sub-goals (e.g., Koechlin et al., 1999; van den Heuvel

et al., 2003; Ramnani and Owen, 2004). Naturally, our results will need to be confirmed in other deductive contexts, e.g., involving quantifiers or modal operators.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2007.04.069.

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Supplementary materials for

Functional Neuroanatomy of Deductive Inference: A Language-Independent Distributed Network.

By Monti MM, Osherson DN, Martinez MJ & Parsons LM

The supplementary materials are organized in 3 sections, as follows:

1.   Pre-Scan Behavioral Study: Validation of Stimuli Material

We document in a behavioral study the difference in logical complexity within (linguistically matched) pairs of deductive arguments.

2.   Control fMRI Study: Deductive Load vs. Reading Load

In an fMRI experiment we compare the loci recruited by reading load to those recruited by deductive complexity in Experiment I*.

3.   Stimulus Materials from fMRI Experiments I and II

Stimuli used in the two fMRI experiments.

 * NOTE: throughout this document we will refer to the two fMRI experiments presented in Monti *et al*., as Experiment I and Experiment II.

1. Validation of Deductive Load Effect

Four pairs of formal arguments were prepared with the logical structures shown in Table 1, below. They were converted to English by allowing p, q, r to express facts about blocks. The eight arguments fall into four pairs, each pair matched linguistically yet differing in logical complexity. Two of the pairs involve valid arguments, two invalid. (Our use of the terminology *valid* and *invalid* conforms to sentential logic. We chose arguments whose logical status does not depend on the choice of "inclusive" versus "exclusive" interpretation of disjunction.) The colors, shapes, and sizes used to instantiate p, q, r were chosen randomly for each argument, under the constraint that different choices be made for simple versus complex arguments in a given pair. In what follows, a particular choice of colors, shapes, and sizes for each of the eight arguments is termed an "instantiation."

Logical Status			Formal Argument	Sample Instantiation
Valid	Pair 1	Simple	$p \rightarrow \neg q$ p $\neg q$	If the block is green then it is not round. The block is green. The block is not round.
		Complex	$p \rightarrow \neg q$ q $\neg p$	If the block is large then it is not blue. The block is blue. The block is not large.
	Pair 2	Simple	$(p \vee q) \rightarrow \neg r$ p $\neg r$	If the block is either round or large then it is not blue. The block is round. The block is not blue.
		Complex	$(p \vee q) \rightarrow \neg r$ r $\neg q$	If the block is either red or round then it is not large. The block is large. The block is not round.
Invalid	Pair 3	Simple	$(p \wedge q) \rightarrow \neg r$ p $\neg r$	If the block is both blue and square then it is not large. The block is blue. The block is not large.
		Complex	$(p \wedge q) \rightarrow \neg r$ r $\neg p$	If the block is both square and small then it is not blue. The block is blue. The block is not square.
	Pair 4	Simple	$\neg p \rightarrow (q \vee r)$ $\neg p$ q	If the block is not red then it is either square or small. The block is not red. The block is square.
		Complex	$\neg p \rightarrow (q \vee r)$ $\neg q$ p	If the block is not round then it is either blue or small. The block is not blue. The block is round.

Table 1. The fourth and fifth columns report the pairs of formal arguments and a sample instantiation for each.

Methods

Thirty-five undergraduates at Rice and Princeton Universities were recruited to evaluate the 8 arguments and judge their difficulty. It was explained that: "The arguments all concern blocks stored in a box. The blocks come in different colors, sizes, and shapes. The premises of a given argument give you information about just one of the blocks (called 'the block'). You must accept this information as true, then decide whether the conclusion (which refers to the very same block) is forced to be true". Participants then carried out four tasks in the following order. First, they reviewed all eight arguments within one instantiation without time pressure. Then they categorized a new instantiation of each argument as valid or invalid as fast as possible (compatibly with confidence in the judgment). Next, they rated another instantiation of the arguments on a scale from 1 to 7 according to the following instructions. "Use values close to 1 for arguments whose status is easy to recognize. Use values close to 7 for arguments whose status is hard to recognize. Use intermediate values in the obvious way". For analysis, numbers were rescaled to run between 1 and 100. Finally, under a new instantiation, respondents were presented with each pair of arguments (as grouped in Table 1) and asked to "indicate which argument in a given pair is more difficult for you to evaluate". Four additional pairs of arguments (with formal structures similar to those in Table 1) were inserted as "fillers" to bring the number of items to eight (as with the other tasks). Items were presented in individually randomized order; in the last task, the left-right position of arguments in a pair was also determined randomly. Feedback about the validity of a given argument was never provided.

Results

The results for the last three tasks are shown in Figures 1a,b,c. Arguments hypothesized to be the more difficult member of their pair (i.e. marked "complex" in Table 1) took longer, were rated as more

difficult, and were more often chosen as difficult (see Figures 1a,b,c, respectively). Differences are

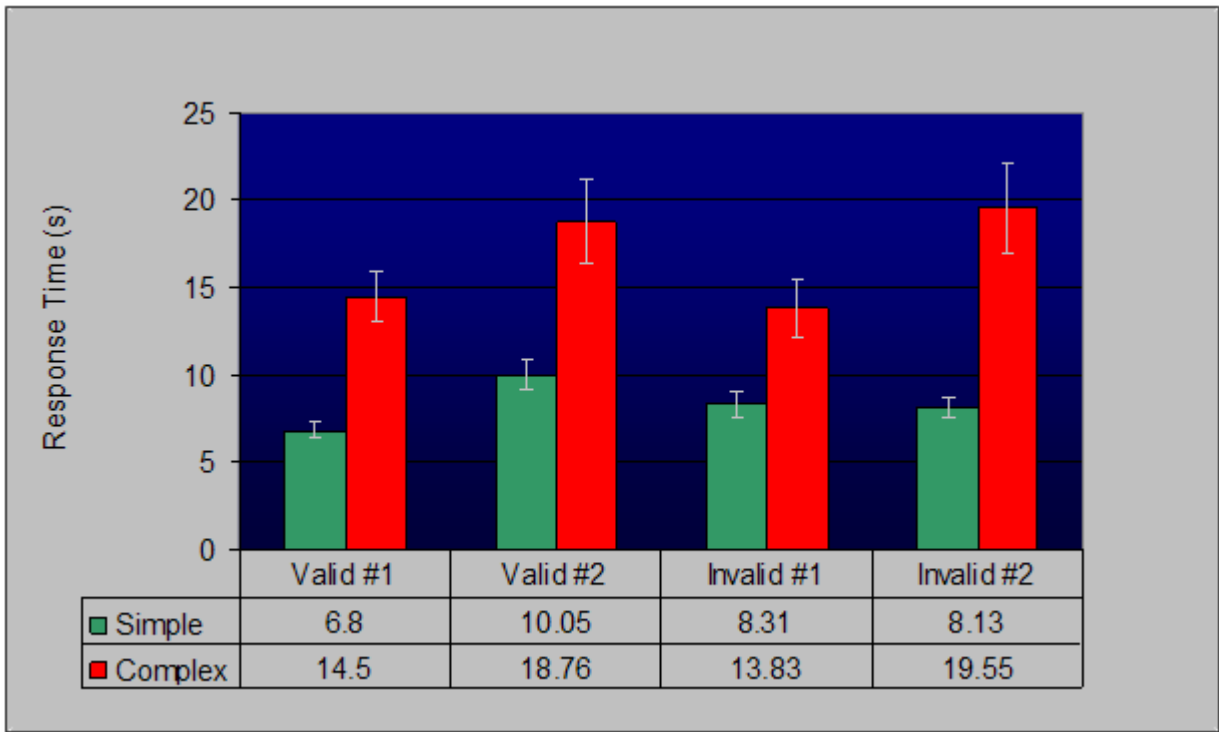reliable for all four pairs of arguments (by correlated *t*-test and binomial test).

	Valid #1	Valid #2	Invalid #1	Invalid #2
Simple	6.8	10.05	8.31	8.13
Complex	14.5	18.76	13.83	19.55

Figure 1a. Response-Time data for assessment of logical status of arguments.

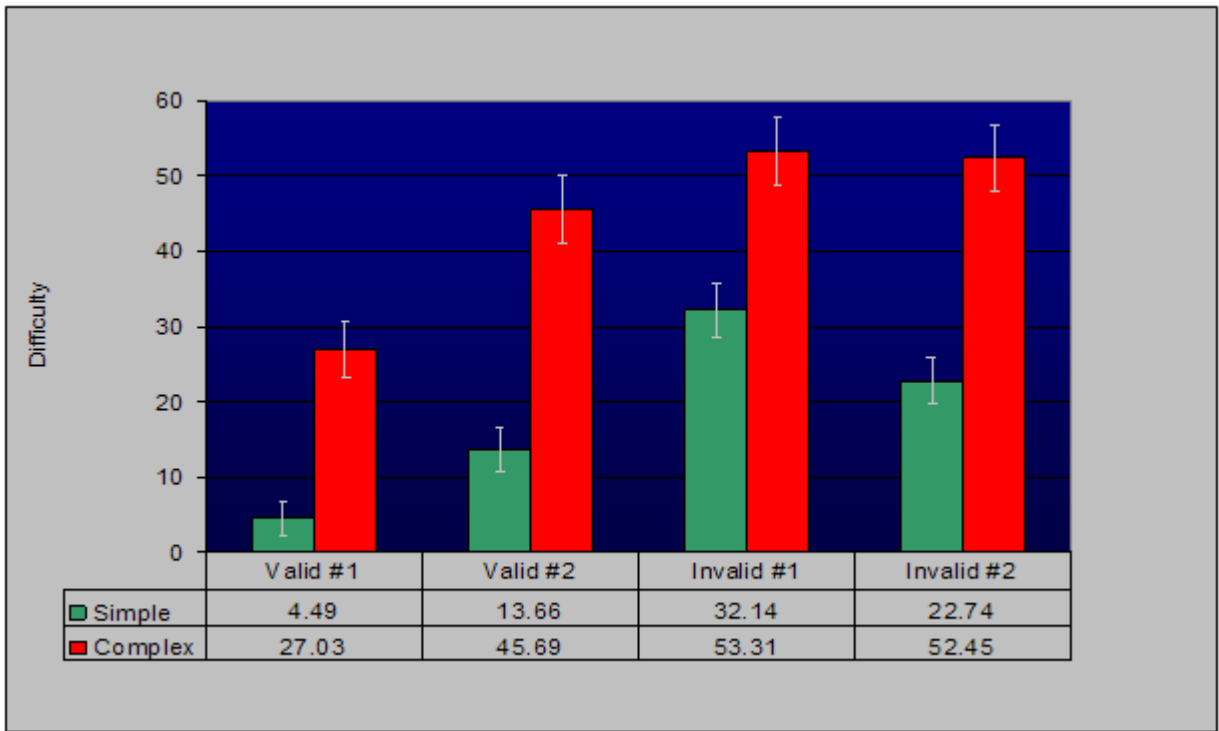|	Valid #1	Valid #2	Invalid #1	Invalid #2
Simple	4.49	13.66	32.14	22.74
Complex	27.03	45.69	53.31	52.45

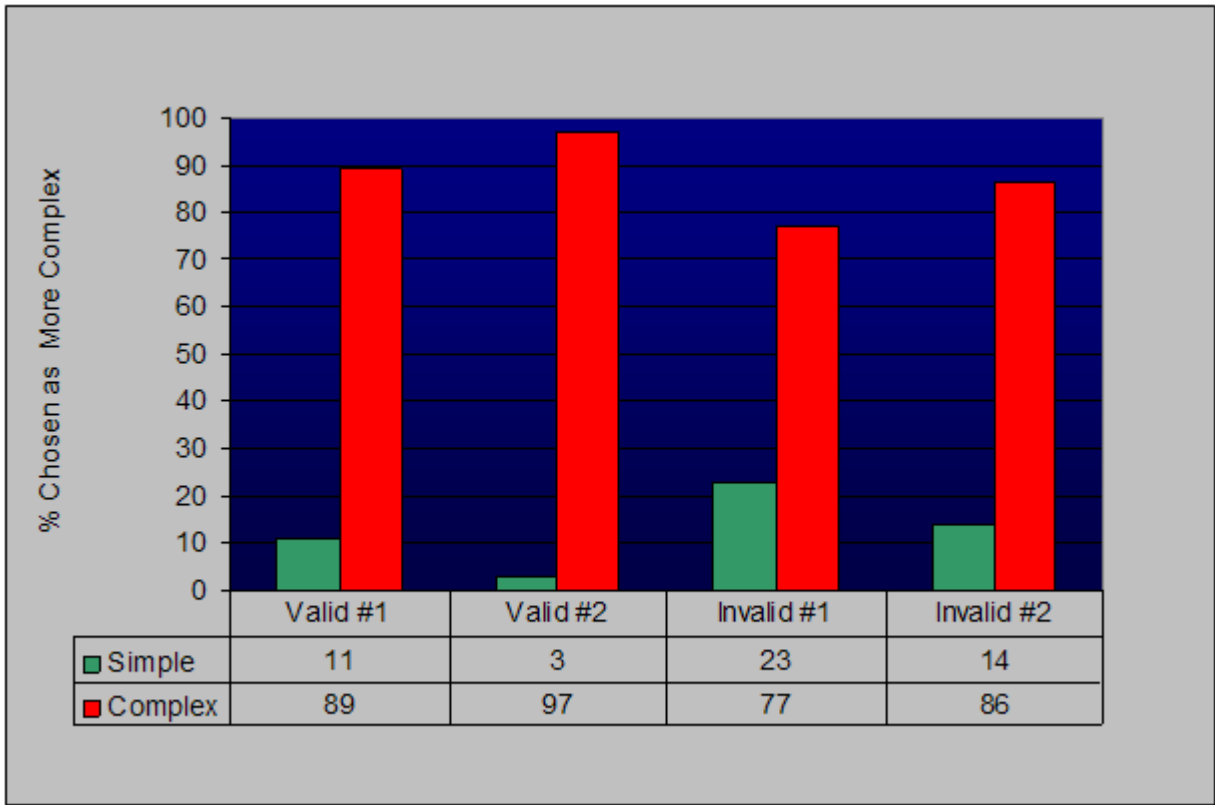**Figure 1b.** Difficulty rating of arguments.

Figure 1c. Relative complexity pairwise choice.

The behavioral study was repeated with eight new subjects, using pseudo-words rather than features of blocks. The data again show that "difficult" arguments in each pair require longer time for evaluation, are rated as harder, and chosen as more difficult in direct comparison.

2. Reading Load vs. Logic Load

Compared to their simple counterparts, complex arguments may have elicited more reading (or re-reading). It is thus important to assess whether increased reading per se -- in the absence of deductive reasoning -- contributes to the activation of candidate core areas for deduction. The present study was designed to identify brain loci responding to increased reading load alone. Participants in this fMRI study read statements (drawn from arguments of Experiment I) presented at either a slow or fast rate. Areas specialized for reasoning should not be visible in the reading load contrast.

Materials and Methods

Subjects

Eight right-handed and native English speaker volunteers (4 female) participated for compensation after signing informed consent. All participants were Princeton University students who reported no formal training in logic.

Stimuli

By recombining the same propositions used in the *blocks* condition sessions of Experiment I we constructed a list of 252 statements. Statement involving "if … then" were always followed by two shorter ones (as in the arguments of Experiment I). The ordering excluded any logical relatedness between adjacent statements. Deductive reasoning was therefore not performable.

 Experimental Design and Procedure

In each trial of 14 s, participants were asked to read for comprehension either six (slow condition) or twelve (fast condition) statements, presented serially, one at a time. No response was required. In slow

trials, conditional statements (long) were displayed for 3,500 ms whereas short statements were presented for 1750 ms each. In fast trials, half this time was allotted to each statement thereby requiring twice as much reading. Each trial was followed by 12 s of fixation, then a two-second cue indicating whether the next trial was fast or slow. Fast and slow trials were alternated randomly, then the entire sequence repeated in a different order. The 56 total trials were administered in two scans, each 6 min and 40 s long.

fMRI Data Acquisition and Analysis

Functional and structural data were acquired with identical parameters to Experiment I. Pre-processing and analysis methods exactly followed those used in Experiment I. Group analyses, however, were carried out with much more liberal statistical methods so to yield more stringent test of the hypothesis that core regions of Experiment I reflect reading load. First, a fixed-effects model was used for the aggregate analysis. As observed by Penny et al. (2003), a fixed-effects model is sensitive enough for the activations of one subject, out of a sample of five, to be preserved in the group statistic. Second, contrasts were thresholded using a cluster size significance level of $P < 0.05$ corrected (compared to $P < 0.001$ corrected, in Experiment I). The use of such liberal statistics made our analysis overly sensitive and biased towards finding even a subtle effect, should it be present.

Results

The subtraction of slow from fast reading revealed activity in several regions (Table 2 and Fig. 2) across the cerebrum and cerebellum. Occipital cortex exhibited active clusters in bilateral lingual (BA17) and middle occipital (BA18) gyri, along with left cuneus (BA18). Parietal cortex was primarily engaged bilaterally in superior parietal lobules (BA7) and in left precuneus (BA7) and inferior parietal lobule (BA40). Bilateral, predominantly left, foci were active across temporal cortex in middle and

superior temporal gyri (spanning BA21, BA22, and BA37). Frontal cortex was activated in bilateral

middle and inferior frontal gyri (BA6 and BA9, respectively), along with left superior frontal (BA6,

pre-SMA) and precentral (BA6), and right middle frontal (BA9) gyri. As shown in Figure 2 the overlap

between the regions engaged by the logic load and the reading load is restricted to small regions in

bilateral middle frontal gyrus (BA6). Thus, the candidate areas for core deductive operations were not

recruited by differential reading load (see Fig. 2 in Monti *et al.*, and Table 5 below, for comparison).

Moreover, the pattern of activations here is similar to that isolated by the reading contrast in

Experiment I. The fact that areas such as dorsolateral BA6 and left parietal cortex (BA40, BA7) were

active for reading load without deduction is consistent with our interpretation that they "support"

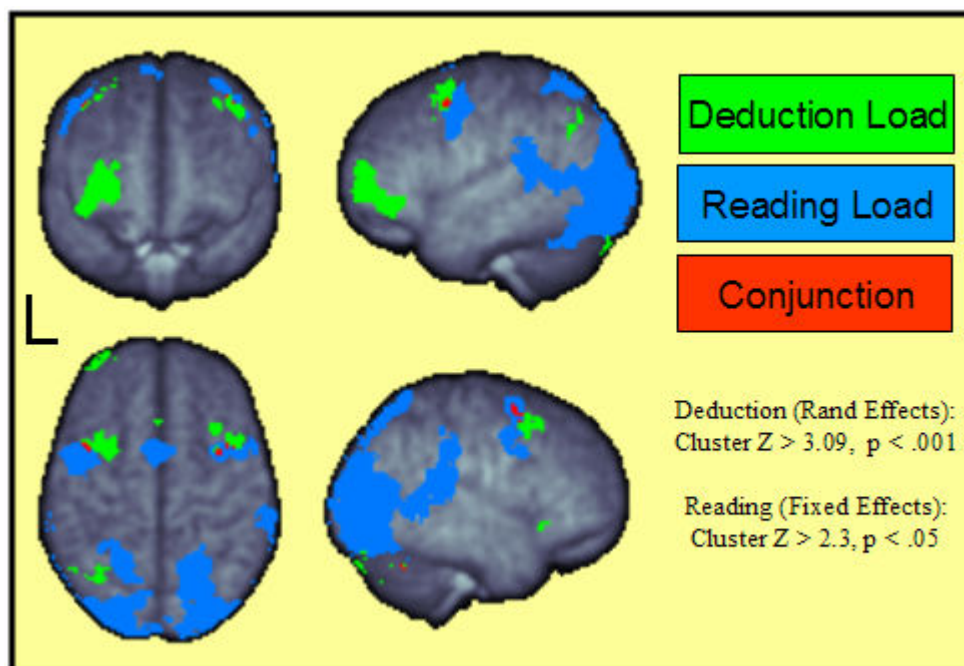deductive reasoning rather than execute its core operations (see Discussion in Monti *et al.*).

Figure 2. Overlay of activations in the Logic Load (Experiment I) and the Reading Load conditions.

| MNI Coordinates | | | | Z |
x	y	z	Region Label (BA)	Score
Frontal				
-4	6	62	Pre-SMA, Superior Frontal Gyrus (6)	6.67
-48	2	58	Middle Frontal Gyrus (6)	5.88
-56	4	46	Middle Frontal Gyrus (6)	5.61
-42	-6	50	Precentral Gyrus (6)	5.49
-46	-2	50	Precentral Gyrus (6)	5.28
-34	-6	48	Middle Frontal Gyrus (6)	4.87
48	2	44	Middle Frontal Gyrus (6)	4.41
-54	4	36	Inferior Frontal Gyrus (9)	3.95
40	8	62	Middle Frontal Gyrus (6)	3.85
58	14	40	Middle Frontal Gyrus (9)	3.84
44	6	56	Middle Frontal Gyrus (6)	3.48
56	12	36	Inferior Frontal Gyrus (9)	3.47
Temporal				
50	-42	10	Superior Temporal Gyrus (22)	5.65
66	-40	18	Superior Temporal Gyrus (22)	5.26
-56	-42	20	Superior Temporal Gyrus (22)	4.8
-56	-58	6	Middle Temporal Gyrus (21)	4.59
-62	-40	16	Superior Temporal Gyrus (22)	4.53
-66	-38	20	Superior Temporal Gyrus (22)	4.27
-56	-70	6	Middle Temporal Gyrus (37)	4.13
60	-52	2	Middle Temporal Gyrus (21)	4.09
-58	-52	10	Superior Temporal Gyrus (22)	3.89
54	-60	0	Middle Temporal Gyrus (21/37)	3.83
-60	-64	4	Middle Temporal Gyrus (21/37)	3.79
-60	-42	4	Superior Temporal Gyrus (22)	3.68
Parietal				
-22	-64	58	Superior Parietal Lobule (7)	5.18
-22	-68	58	Superior Parietal Lobule (7)	5.05
-28	-50	58	Inferior Parietal Lobule (40)	4.9
-30	-50	52	Precuneus (7)	4.29
-20	-54	46	Precuneus (7)	2.78
Occipital				
-30	-90	4	Middle Occipital Gyrus (18/19)	8.14
8	-78	-12	Lingual Gyrus (18)	7.32
-8	-86	-12	Lingual Gyrus (18)	7.27
-30	-100	-2	Middle Occipital Gyrus (18)	7.25
36	-88	2	Middle Occipital Gyrus (19)	7.22
-6	-94	2	Cuneus (18)	7.13

Posterior Cerebellum

0	-76	-28	Vermis of VIIAt	6.23
8	-78	-26	Crus I	6.03
34	-62	-32	Lobule VI	5.85
-36	-62	-30	Crus I	4.11

Table 2. Activations for fast minus slow reading.

Reference

Penny, W.D., Holmes, A.P., Friston, K.J. (2003) Random effects analysis. In Frackowiak, R.S., Friston, K.J., Frith, C.,

   Price, C.J., Zeki, S., Ashburner, J. & Penny, W.D. (eds) *Human Brain Function*. Academic Press, 2nd Edition.

3. Stimuli

Table 3a. Stimuli used in Experiments I (blocks, pseudo-words).

Blocks Condition	Pseudo-Words Condition
If the block is red then it is not square. The block is red. -- The block is not square.	If there is tuk then there is no rop. There is tuk. -- There is no rop.
If the block is round then it is not blue. The block is blue. -- The block is not round.	If there is bep then there is no rop. There is rop. -- There is no bep.
If the block is either square or small then it is not green. The block is square. -- The block is not green.	If there is either rop or sem then there is no bep. There is rop. -- There is no bep.
If the block is either green or round then it is not large. The block is large. -- The block is not round.	If there is either rek or rop then there is no sem. There is sem. -- There is no rop.
If the block is both red and square then it is not small. The block is red. -- The block is not small.	If there is both bep and gez then there is no sem. There is bep. -- There is no sem.
If the block is both round and large then it is not red. The block is red. -- The block is not round.	If there is gez and sug then there is no bep. There is bep. -- There is no gez.
If the block is not blue then it is either round or small. The block is not blue. -- The block is round.	If there is no rek then there is either gez or sug. There is no rek. -- There is gez.
If the block is not square then it is either green or large. The block is not green. -- The block is square.	If there is no rop then there is either bep or sug. There is no bep. -- There is rop.

Table 3b. Stimuli used in Experiments I (faces, houses).

Faces Condition	Houses Condition
If he has open eyes then he doesn't have a frown. He has open eyes. ————————————— He doesn't have a frown.	If it has a bay window then it has no garage. It has a bay window. ————————————— It has no garage.
If he has open eyes then he doesn't have a frown. He has a frown. ————————————— He doesn't have open eyes.	If it has a front stoop then it has no garage. It has a garage. ————————————— It has no front stoop.

If he has either a frown or a small nose then he
    doesn't have thin eyebrows.
He has a frown.
—————————————
He doesn't have thin eyebrows.
	If it has either a garage or a chimney then it has no front
	    stoop.
	It has a garage.
	—————————————
	It has no front stoop.

If he has either thin eyebrows or a smile then he
    doesn't have a long nose.
He has a long nose.
—————————————
He doesn't have a smile.
	If it has either a double door or a garage then it has no
	    has a chimney.
	It has a chimney.
	—————————————
	It has no garage.

If he has both open eyes and a frown then he doesn't
    have a small nose.
He has open eyes.
—————————————
He doesn't have a small nose.
	If it has both a front stoop and a pitched roof then it has
	    no chimney.
	It has a front stoop.
	—————————————
	It has no chimney.

If he has both a smile and a long nose then he doesn't
    have open eyes.
He has open eyes.
—————————————
He doesn't have a smile.
	If it has a pitched roof and brick siding then it has no
	    front stoop.
	It has a front stoop.
	—————————————
	It has no pitched roof.

If he doesn't have bushy eyebrows then he has either
    a smile or a small nose.
He doesn't have bushy eyebrows.
—————————————
He has a smile.
	If it has no double door then it has either a pitched roof
	    or brick siding.
	It has no double door.
	—————————————
	It has a pitched roof.

If he doesn't have a frown then he has either thin
    eyebrows or a long nose.
He doesn't have thin eyebrows.
—————————————
He has a frown.
	If it has no garage then it has either a front stoop or
	    brick siding.
	It has no front stoop.
	—————————————
	It has a garage.