◆ **Human Brain Mapping 31:1430–1445 (2010)** ◆

Conditional and Syllogistic Deductive Tasks Dissociate Functionally During Premise Integration

Carlo Reverberi,[1,2,3]* Paolo Cherubini,[1] Richard S.J. Frackowiak,[2,4] Carlo Caltagirone,[2] Eraldo Paulesu,[1] and Emiliano Macaluso[2]

[1]*Department of Psychology, Università Milano - Bicocca, Milano, Italy*
[2]*Neuroimaging Laboratory, Santa Lucia Foundation, Roma, Italy*
[3]*Bernstein Centre for Computational Neuroscience, Charité-Universitätsmedizin, Berlin, Germany*
[4]*Centre Hospitalier Universitaire Vaudois, Université de Lausanne, Switzerland*

Abstract: Deduction allows us to draw consequences from previous knowledge. Deductive reasoning can be applied to several types of problem, for example, conditional, syllogistic, and relational. It has been assumed that the same cognitive operations underlie solutions to them all; however, this hypothesis remains to be tested empirically. We used event-related fMRI, in the same group of subjects, to compare reasoning-related activity associated with conditional and syllogistic deductive problems. Furthermore, we assessed reasoning-related activity for the two main stages of deduction, namely encoding of premises and their integration. Encoding syllogistic premises for reasoning was associated with activation of BA 44/45 more than encoding them for literal recall. During integration, left fronto-lateral cortex (BA 44/45, 6) and basal ganglia activated with both conditional and syllogistic reasoning. Besides that, integration of syllogistic problems additionally was associated with activation of left parietal (BA 7) and left ventro-lateral frontal cortex (BA 47). This difference suggests a dissociation between conditional and syllogistic reasoning at the integration stage. Our finding indicates that the integration of conditional and syllogistic reasoning is carried out by means of different, but partly overlapping, sets of anatomical regions and by inference, cognitive processes. The involvement of BA 44/45 during both encoding (syllogisms) and premise integration (syllogisms and conditionals) suggests a central role in deductive reasoning for syntactic manipulations and formal/linguistic representations. *Hum Brain Mapp 31:1430–1445, 2010.* © 2010 Wiley-Liss, Inc.

Key words: fMRI; rules; logic; language; Broca's area; abstract thinking

INTRODUCTION

Deductive reasoning allows us to draw consequences (conclusions) from previous knowledge (premises). Important for developing formal science, it is all the more important for everyday thinking, as it underlies the drawing of explicit forecasts and expectations that drive behavior. Experimental cognitive psychology has investigated deduction by means of three main classes of deductive problems: (A) *propositional* reasoning problems using logical connectives such as "if . . . then" (i.e. conditional problems), "either . . . or" (i.e. disjunctive problems), "and,"

Additional Supporting Information may be found in the online version of this article.

Contract grant sponsor: Wellcome Trust Programme Grant.

*Correspondence to: Carlo Reverberi, Department of Psychology, Università Milano Bicocca, Piazza Ateneo Nuovo, 1, Milano 20126, Italy. E-mail: carlo.reverberi@unimib.it

Received for publication 25 December 2008; Revised 1 October 2009; Accepted 16 October 2009

DOI: 10.1002/hbm.20947

"not," whose logic is best described by propositional calculus; (B) reasoning problems using *quantified* predicative statements, such as "all X are Y" or "no X are Y," whose logic is best described by predicate calculus; this sort of problem is typically referred to as an "Aristotelian" or "categorical" syllogism; (C) a large class of *relational* problems, some involving linguistic and others pictorial premises all of which involve descriptions of extra-logic relationships between terms (e.g., spatial relationships, temporal relationships, quantities, etc.).

Irrespective of problem type, deductive reasoning always entails first the representation of a set of premises that are then integrated in order to draw some conclusion [e.g., Braine and O'Brien, 1998; Johnson-Laird and Byrne, 1991]. A fundamental unresolved question is whether the same mental representations and integration processes underlie different types of deductive problems, or whether different processes are engaged depending on the specific type of problem. This study addresses this issue for conditional problems and quantified syllogisms (Types A and B above). Conditionals and quantifiers are involved in most deductive arguments, both in formal settings and in everyday reasoning. Their importance is mirrored by the interest they have aroused both in logic and in psychology. The use and meaning of "if" is probably the most debated issue in the history of logic [Woods et al., 1997]. One common way of dating the beginning of modern logic is by reference to Frege's introduction of quantification theory, in 1879 [Jager, 1972]. Similarly, the original cores of two most influent psychological theories of deduction [i.e., "mental models theory," Johnson-Laird and Byrne, 1991; and "mental logic theories" Braine and O'Brien, 1998] dealt exclusively with problems involving propositional connectives and quantifiers.[1] Among connectives, both theories devote special attention to conditionals [Byrne and Johnson-Laird, 2009]. These two theories assume that a common cognitive mechanism underlies conditional and syllogistic reasoning. Conditional and syllogistic premises would be represented in the same format: an analogical representation of meaning for the mental models theory, or syntactic strings for the mental logic theory. Premises would then be integrated by combinatorial processes in mental models theory, or by applying transformational rules in mental logic theory, irrespective of problem type.

However, behavioral studies have also described distinct reasoning strategies for specific types of deductive problem [e.g., Roberts, 2004]. For example, strategies based on Euler's or Gergonne's circles [Erickson, 1974; Politzer et al., 2006] or characteristic diagrams [Stenning and Oberlander, 1995] have been described for syllogisms; the effect of lexical marking [Clark, 1969] and of anchoring to linear representations [De Soto et al., 1965] has been described specifically for relational problems; while probabilistic assumptions about the extension of classes has been found to affect reasoning with conditionals [Evans et al., 2003; Oaksford and Chater, 1994, 2003]. Furthermore, some kinds of problem can be solved using more than one strategy, resulting in systematic inter-individual differences: e.g., for syllogisms, Störring [1908], Ford [1995]. Bacon et al. [2003] found that some people adopted predominantly spatial strategies, while others employed mainly verbal ones. Overall, these findings suggest that there might be some qualitative difference among the representation and integration processes recruited during deductive reasoning either across different classes of problem (e.g. conditional problems versus quantified syllogisms), or across individuals, or both.

Accordingly there is a discrepancy between current cognitive theories of reasoning that postulate common mechanisms irrespective of problem type [Braine and O'Brien, 1998; Johnson-Laird and Byrne, 1991] and neuroimaging data that have often revealed differential neural substrates depending on problem type [Fangmeier et al., 2006; Goel et al., 2000, 2004; Goel and Dolan, 2001, 2003; Knauff et al., 2003; Reverberi et al., 2007]. However, it should be noted that these associations and dissociations in the brain imaging literature have been typically inferred on the basis of qualitative comparisons across studies, rather than by direct testing within the same experiment in the same group of subjects. Thus, it is difficult to evaluate the actual implications of imaging data on current cognitive theories of reasoning.

Our central aim here was to provide direct evidence of association and/or dissociation of reasoning-related activations for different types of reasoning problems, specifically conditional and syllogistic problems. Critically, we compared problems solved by the same participants, within the same experimental paradigm, and with stimuli that share similar superficial features. In this way we were able to remove any potential confounds introduced by differences in paradigms/stimuli and by the use of different participants, which could each account for some of the problem specific activations reported in previous neuroimaging experiments [e.g., Monti et al., 2007; Reverberi et al., 2007]. Furthermore, a within-participants design allowed formal testing for differences between activation patterns associated with the different types of deductive problem. To date, such evidence is still unavailable.

A second issue that we addressed concerns the neural correlates of the subprocesses thought to engage at different stages of deductive problem solving. Mental models and mental logic theories [Braine and O'Brien, 1998; Johnson-Laird and Byrne, 1991; Rips, 1994] propose that deduction is a multistage process, in which the first stage is an encoding of premises in working memory, and the second consists of the integration of premises to generate a

---

[1] Even though they originally focused mostly on propositional and quantified reasoning, both theories have also devised explanations of how they can account for relational reasoning as well. For mental models theory, see e.g. Goodwin and Johnson-Laird [2005]. The mental logic approach allows introducing formal *meaning postulates* for solving relational problems [Braine and O'Brien, 1998; Rips, 1994]. Specific implementations of rule based theories dealing with of relational reasoning were devised by Hagert [1984] and Ohlsson [1984].

TABLE I. Example of the different type of problems used in the study

	Integrable	Nonintegrable
Quantified	P_1 Every thing x is y P_2 Every thing y is z	P_1 Every thing x is y P_2 Every thing z is s (P_3 Every thing s is t)
Conditional	P_1 If a thing is x then is y P_2 If a thing is y then is z	P_1 If a thing is x then is y P_2 If a thing is z then is s (P_3 If a thing is s then is t)

Letters written in *italics* stand for a bisyllabic Italian nonword such as "rufa." The nonwords are in adjectival position and agree with the gender of the word "thing" (feminine in Italian). The nonintegrable sentences can be made by two or three sentences. When present, the third sentence is always integrable with the second.

conclusion whenever possible. This view is widely shared by other scholars, who conceive of mental representations and the processes that act upon them as discrete—albeit linked—components of deduction [e.g., Stenning and Monaghan, 2004]. In this study, we separately assessed the encoding and integration stages of both propositional (conditional) and quantified (syllogistic) arguments. This further evidence is important given that it cannot be safely assumed that different classes of deductive reasoning produce the same activation patterns in the two main processing stages.

The *encoding stage* was investigated by comparing brain activity when volunteers read a sentence with the explicit aim of then using it for reasoning (first premise of the argument), versus reading of the very same sentence to remember it literally. This allowed us to investigate whether encoding for reasoning requires different representations (e.g., representing deep structural features) than encoding for literal recall. Furthermore, we compared directly conditional and syllogistic first premises, thus testing for selective processes for one or the other type of problem at the encoding stage. The *integration stage* of deductive reasoning was investigated by measuring activation patterns elicited by the second premise of an argument. We compared second premises that could be integrated with the first premise (thus yielding a conclusion), with literally identical premises that could not be integrated (i.e. the same second premise but now following a different, unrelated first premise).

These procedures allowed mapping of the encoding and integration stages of reasoning to their specific neural substrates. Comparisons of these patterns of activation for conditional and syllogistic premises permitted a comprehensive examination of the similarities and differences between the neural correlates of propositional and quantified reasoning both at the encoding and at integration stages of the reasoning cascade.

METHODS

Participants

Twenty-six healthy subjects (aged 25 years on average, SD: 5.0; 15 males) participated in the experiment. After instruction in the procedure, all participants gave written informed consent. All were right-handed, had normal vision, with no neurological or psychiatric history. The absence of gross structural brain abnormalities was checked on structural scans. The study was approved by the Santa Lucia Foundation (Scientific Institute for Research Hospitalization and Health Care) independent Ethics Committee.

Stimuli

One hundred thirty-two deductive problems and 40 memory trials were administered to participants during fMRI scanning. Among the 132 deductive problems, 72 were categorical syllogisms and 60 were conditional problems. The deductive problems consisted of two factors—integrability (integrable vs. nonintegrable premises) and type of sentence (syllogistic vs. conditional problems).

Each deductive problem consisted of two or three premises and a set of four alternative conclusions (Table I and Fig. 1). All sentences described the qualities of an unspecified "thing" by means of nonexistent two-syllabic adjectives with a plausible phonological structure in Italian. For example: "ogni cosa rufa è tenna" (i.e. "every rufa thing is tenna"), where "cosa" means "thing," "ogni" means "every," "è" means "is," and "rufa" and "tenna" are two nonwords. The second premise (P_2) was crucial for deductive problems. It could be *integrable* (48 syllogistic and 38 conditional problems) or *nonintegrable* (24 syllogistic and 22 conditional problems), depending on whether it shared an adjectival term with the first premise (P_1) or not. The presence of a common term (Table I) allowed the generation of a deductive conclusion from P_1 and P_2. All integrable P_2 were directly followed by four conclusions, from which participants had to choose the valid one rapidly. When P_2 was *nonintegrable*, preventing generation of a valid conclusion from P_1 and P_2, the correct answer on presentation of the four alternative statements was "nothing follows" (this occurred in 14 syllogistic and 12 conditional problems). However, in 10 syllogistic and 10 conditional trials, a nonintegrable P_2 was followed by a third premise, P_3, that was *always* integrable with P_2 and hence allowed a conclusion from them. In those trials, the four alternative statements were given directly after P_3 for a choice to be made. Subjects were informed about this feature of the design and were told that when P_2 was nonintegrable, they no longer needed to keep P_1 in mind but had to memorize P_2 because it could be followed by a P_3 that allowed a conclusion. This manipulation was introduced to ensure that

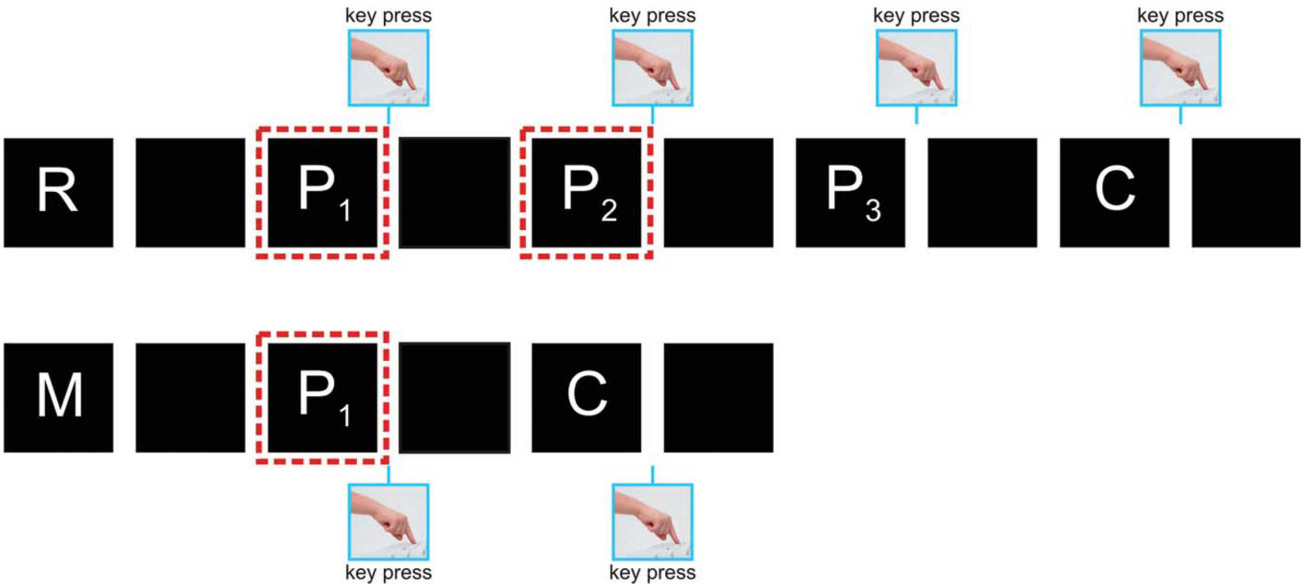

Figure 1.

Scheme of stimulus presentation for a reasoning trial (top panel) and a memory trial (bottom panel). R: cue in reasoning trials; M: cue in memory trials; P: Premises; C: Conclusions. Each keypress was followed by the presentation of a blank screen for 2 s. Only the BOLD signal associated with the presentation of the first and the second sentences (see dashed lines) was used for statistical inference. Thus, activity associated with the choice between alternative conclusions and the presentation of the third sentence (when applicable) were not included in the fMRI group analyses.

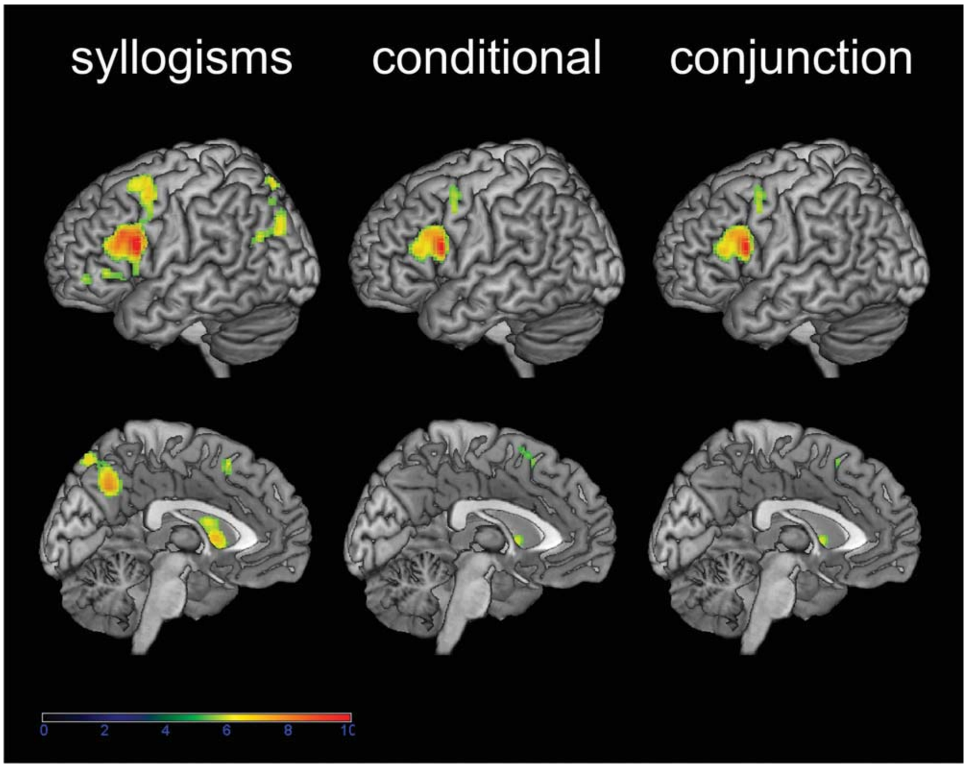

Figure 2.

Brain areas activated during integration of deductive premises (P_2) rendered onto a T1-weighted brain image ($P < 0.05$, corrected for multiple comparisons). In the left panel, integration effect on syllogistic problems; in the middle panel integration effect on conditional problems, and in the right panel the brain areas in which both effects are present (conjunction analysis). Color scale (*t*-values) on the bottom-left.

TABLE II. Reaction times (milliseconds) and accuracy (proportion of correct responses)

	RT P_1	RT P_2 integrable	RT P_2 nonintegrable	RT C	Accuracy integrable	Accuracy nonintegrable
Reasoning						
Syllogisms	2913 (749)	3983 (860)	3143 (854)	2321 (433)	0.75 (0.16)	0.83 (0.10)
Conditionals	3304 (825)	3341 (854)	3378 (853)	2950 (680)	0.78 (0.12)	0.86 (0.11)
Memory						
Syllogisms	2615 (599)			2379 (317)	0.94 (0.07)	
Conditionals	3007 (756)			2774 (341)	0.94 (0.06)	

RT, reaction time; P_1, P_2, first and second premise; C, conclusion.
For reaction times only correct trials are considered.

subjects processed the nonintegrable P_2 fully (see the procedure later).

For integrable *conditional problems*, we used the following three logical forms (for the sake of clarity nonwords have been substituted by letters):

Conditional$_1$: P_1 If a thing is x then it is y
P_2 If a thing is y then it is z
Correct conclusion: If a thing is x then it is z

Conditional$_2$: P_1 If a thing is x then it is y
P_2 If a thing is x then it is z
Correct conclusion: If a thing is x then it is y and z

Conditional$_3$: P_1 If a thing is x then it is z
P_2 If a thing is y then it is z
Correct conclusion: If a thing is x or y then it is z

Categorical syllogisms were also administered. For example:

P_1 Everything x is y
P_2 Nothing y is z
Correct conclusion: Nothing x is z

In general, a categorical syllogism consists of two premises (P_1 and P_2 in the example) followed by a conclusion. The two premises make assertions about class relationships among three terms (x, y, and z in the example), one of which is common to the two premises (the *middle* term, y in the example). Syllogisms differ depending on two main properties. First, the type of premise (P_1 and P_2): universal affirmative ("every x is y"), universal negative ("no x is y"), particular affirmative ("some x is y"), and particular negative ("some x is not y"). Second, the position of the middle term in each premise (this property is called the *figure* of the syllogism) can be varied four ways. Combining the different levels of these two factors, 64 different categorical syllogisms can be devised. Among these, we were mainly interested in syllogisms that can be rapidly and correctly solved by most people. Thus, we selected a subset of nine syllogisms[2] (Table I for an example) from the easy end of the spectrum of syllogism types [Dickstein, 1978]. These syllogisms are similar to those used in most preceding studies in the neuroimaging field [Goel et al., 2000; Goel and Dolan, 2003, 2004]. However, it has been pointed out that easy syllogisms can also be correctly solved by means of simple nonlogical heuristics, e.g., the atmosphere heuristic [Reverberi et al., 2009a]. To prevent this possible confound, we introduced a further set of syllogistic problems[3] that cannot be correctly solved in this way. Thus, during training (see later, procedure), subjects realized that use of the atmosphere heuristic was *not* a viable strategy for correctly solving all items. This tended to prevent them from using this strategy during subsequent fMRI scanning. Overall, during *f*MRI scanning, 48 *integrable* syllogistic problems were administered: of these, 24 problems were similar to those used in preceding studies (henceforth "the main set," used for the main neuroimaging analyses) and 24 belonged to our newly introduced nonheuristic set.

Memory trials were included as baseline for the encoding stage of reasoning trials. They contained only one sentence (P_1), followed by a set of four alternative answers. The single premise was either a conditional ($n = 20$) or a quantified ($n = 20$) statement, with the same sentence structure as used in deductive problems.

Procedure

The experiment was carried out in Italian under the control of a personal computer running Presentation™ experimental software (www.neurobs.com). Subjects were informed they would do either a "reasoning" or a "memory" task, depending on the letter presented at the beginning of each trial ("R" for a reasoning and "M" for a memory trial, Fig. 1).

In reasoning trials, the task was identical in all problem types. Participants were required to solve a deductive problem involving a series of premises about imaginary features of objects. All the premises (i.e. P_1, P_2, plus sometimes P_3) were to be assumed true. Participants were asked to read each premise and whenever possible, to

---

[2] Specifically we used syllogisms of the following types [reported in standard notation, see Dickstein, 1978]: aa4, ae2, ae4, ai1, ai3, ea1, ea2, ia3, ia4. All of these syllogisms have a valid solution.

[3] The syllogisms that could not be solved by means of simple nonlogical heuristics were aa2, aa3, ae1, ai2, ea4, and ia2.

draw a new conclusion promptly and accurately. At the end of each trial, subjects were asked to recognize their inferred conclusion. Participants were told that if they were unable to reach a conclusion on P_2, they should nevertheless read and remember it carefully because P_2 could be critical for establishing a conclusion with a P_3 if such occurred. This requirement was designed to force subjects to process P_2 fully (reading, encoding) even when P_2 could not be integrated with P_1. Furthermore it introduced a need to update the content of working memory even in the case of nonintegrable P_2 stimuli, thus equating the working memory requirements of integrable and nonintegrable conditions.

In memory trials, subjects were told to read and remember sentences carefully for fast recognition from among four subsequently presented sentences.

Each reasoning trial started with a central cue ("R") lasting one second (Fig. 1). After a delay lasting on average 3 s (range 2–4 s), the premises (P_1, P_2 and, in some trials, P_3) were shown serially, one at a time. No constituents of a problem (premises or conclusions) ever appeared together (Fig. 1). The presentation rate was in part controlled by participants who were required to press a key (with the right index finger) as soon as they were ready to proceed to the next premise (P_2, P_3) or conclusion. Once participants pressed the key, a blank screen (the interstimulus delay) followed for 2 s (see Fig. 1). The maximum time available for processing each premise was 8 s. If the key was not pressed before this deadline, a trial was interrupted and scored incorrect. After a delay following the final premise (P_2 or P_3) a question mark was presented for 0.4 s, anticipating the presentation of four alternative and numbered conclusions. Participants had to recognize as rapidly as possible the one that was *identical* to their own conclusion from among the four alternatives. Subjects responded using an MR compatible button box (answer 1: left middle finger; 2: left index finger; 3: right index finger; 4: right middle finger). Time granted for answering at this stage depended on the stimulus type: 3 s for syllogisms and 5 s for conditional sentences. Conditional problems had longer time windows because the conclusion could be longer and more linguistically complex than conclusions to categorical syllogisms. It is important to note that these short time windows were barely enough to recognize a target sentence among three distracters. Because of the strict time limitation, we plausibly assumed that no further reasoning was possible at the stage of conclusion recognition. In this way, participants were forced to produce relevant inferences during P_2 processing (or P_3 processing, in some nonintegrable problems). The overall duration of each trial ranged from a theoretical minimum of 6.8 s to a maximum of 37.8 s, depending on how fast participants processed the premises and drew conclusions. The average duration of a trial across participants and problem types was 20.4 s (SD = 4.0 s).

The memory trials began with a central cue ("M") presented for 0.4 s followed by a delay lasting on average 3 s (2–4 s range). Participants were then presented with either a conditional or a quantified statement (P_1). They had to press a key as soon as they were ready to proceed to the next phase. Again, a maximum of 8 s was allowed after which the trial was interrupted and marked incorrect. Once participants pressed a key, a question mark was shown for 0.4 s. Four alternative and numbered sentences followed. The task of each participant was to choose the sentence identical to P_1 and to press the corresponding key (maximum response time 5 s). The overall duration of each memory trial ranged from a theoretical minimum of 4.8 s to a maximum of 20.8 s, depending on how fast participants responded to premises and drew conclusions. The average duration of a trial across participants and problem types was 12.1 s (SD 2.8 s).

The 172 trials of the experimental phase were divided into four separate fMRI runs, with 43 trials for each run. Eighteen of these were syllogistic reasoning problems, 15 were conditional and 10 were memory trials. In each fMRI run, every type of problem was administered in a different randomized order across participants.

Before fMRI scanning, all participants underwent a training session. During training, we presented problems similar to those used during scanning. Training problems tapped the same logical formal structures. They were made superficially different from the experimental ones by changing the nonwords used. Unlike experimental fMRI sessions, subjects received correctness feedback at the end of each trial during training. Furthermore, in case of a wrong answer, the whole problem was presented again and the correct response was shown. The training phase ended either after achieving at least eight correct responses of 10 consecutive trials in both conditional and syllogistic problems of the main-set or after 45 min, irrespective of the performance attained. A minimum of 40 training trials was administered.

Dependent Variables

We considered the following behavioral variables:

1. Average accuracy for conditional and main-set syllogistic problems.
2. *Heuristic index*: proportion of responses that were wrong but *consistent* with the atmosphere heuristic in the nonheuristic set of syllogistic problems. For example, in a problem like: "everything *y* is *x*"; "everything *y* is *z*," the correct answer is "something *x* is *z*." However, the atmosphere heuristic would incorrectly prompt a different choice: namely, "everything *x* is *z*." Of the four alternative conclusions proposed in each problem belonging to the nonheuristic set, only one was consistent with simple atmosphere heuristics, the others were either correct or incorrect, but always inconsistent with the atmosphere heuristic.
3. Reaction times on *integrable* and *non-integrable* sentences for both conditional and syllogistic problems. Only correctly answered trials were used to compute RTs.

TABLE III. Peak activations for the *f*MRI analyses showing significant integration effects

	Laterality	Brodmann area	*x*	*y*	*z*	*Z* score	Cluster size (k)
Conditional problems							
Inferior frontal gyrus	Left	44/45	−50	14	20	7.58	749
Precentral gyrus	Left	6	−50	4	44	5.42	118
Supplementary motor area	Left	6	−8	6	73	5.11	76
Basal ganglia	Left		−18	6	9	5.34	67
Syllogistic problems							
Middle frontal gyrus (orbital portion)	Left	46/47	−46	48	−2	5.07	23
Inferior frontal gyrus	Left	44/45	−50	14	20	>8	1117
Inferior frontal gyrus	Left	45/47	−48	34	2	5.21	46
Middle frontal gyrus	Left	6	−44	6	54	5.69	503
Supplementary motor area	Left	6	−6	18	50	5.51	73
Basal ganglia	Left		−12	12	4	5.85	248
Precuneus	Medial	7	−2	−62	42	6.31	324
Inferior parietal	Left	7	−32	−74	48	4.87	15
Middle occipital gyrus/angular gyrus	Left	39/19	−34	−78	30	5.48	200
Conjunction: syllogistic and conditional problems							
Inferior frontal gyrus	Left	44/45	−50	14	20	7.58	706
Basal ganglia	Left		−18	10	2	5.34	51
Precentral gyrus	Left	6	−48	6	46	5.08	70
Supplementary motor area	Left	6	−6	16	56	5.05	19
Interaction: syllogistic > conditional problems							
Middle occipital gyrus/angular gyrus	Left	39/19	−32	−86	22	4.31	1104
Precuneus	Medial	7	−14	−50	48	4.21	1043

Coordinates [*x*, *y*, *z* in space of Montreal Neurological Institute (MNI) template] and selection of cluster maxima according to the conventions of SPM2.

All the reported main effects are significant $P < 0.05$ corrected for multiple comparisons at voxel level. Interaction effects are significant $P < 0.05$ at cluster level.

Image Acquisition

Imaging was carried out in a 3T Siemens Allegra head scanner (Siemens, Erlangen, Germany). Blood oxygenation level-dependent (BOLD) contrast was obtained using echo planar T2*-weighted imaging (EPI). Acquisition of 32 transverse slices provided coverage of the whole cerebral cortex. Repetition time was 2.08 s, echo time was 30 ms, and in-plane resolution was 3 mm × 3 mm; slice thickness and gap were 2.5 mm and 1.25 mm, respectively.

Data Analysis

Behavioral data were analyzed with the SPSS statistical package. Imaging data were analyzed using SPM2 (www.fil.ion.ucl.ac.uk/spm). The first four image volumes of each run were discarded to allow for stabilization of longitudinal magnetization. Given that our experiment was self-paced, the overall number of volumes available partly depended on the average speed of each subject. Thus, on average 1561 (SD = 116) volumes for each subjects were available for analysis, ranging from a minimum of 1355 volumes to a maximum of 1748. Preprocessing included rigid-body transformation (realignment) and slice timing to correct for head movement and slice acquisition delays. The images were then normalized to MNI space using nonlinear warping implemented in SPM2 using the mean of all functional volumes as a template and then smoothed with a Gaussian filter of 8 mm full-width at half maximum (FWHM) to increase the signal-to-noise ratio and to facilitate group analyses. The time series for each participant was high-pass filtered at 128 s and prewhitened by means of an autoregressive model AR(1) [Friston et al., 2002].

Statistical inferences were based on a random effects approach [Friston et al., 1999; Penny et al., 2004] that comprised two steps. First, the data were best fitted at every voxel for each participant using a combination of effects of interest. The effects of interest were the times of onset of the 18 event types within each of the four *f*MRI-runs. Onsets corresponded to the time of appearance on the screen of the specific stimulus type, delayed by 1 s to take account of the initial reading of sentences. The eight theoretically interesting event types corresponded to cells of the two following factorial designs. The first factorial design considers only P_1 and contains 2 (task type: reasoning *vs*. memory) × 2 (problem type: conditionals *vs*. syllogisms) cells. The second design considers only P_2 and is again a 2 × 2 design with factors integrability (integrable sentence vs. nonintegrable sentence) and problem type (conditionals *vs*. syllogisms). We also modeled events that, while not considered in second-level analyses (see below), may have produced specific hemodynamic responses. These events were the initial cue, the second premise (P_2)

in nonheuristic problems, the third premises (P_3), the question mark and the presentation of alternative conclusions. Five additional factors were used to model error trials separately from correct trials. Thus, 18 conditions were considered overall. All events were modeled as miniblocks of duration corresponding to timing stimuli shown on screen.

All stimulus functions were convolved with the standard SPM2 hemodynamic response function. Linear compounds (contrasts) were used to determine responses for the encoding (P_1: reasoning task > memory task) and integration effects (P_2, integrable > nonintegrable sentences) across fMRI runs in both conditional and syllogistic problems. This resulted in the generation of four contrast images per participant. The two first images concerned the encoding effect, corresponding to these contrasts on P_1: $(\text{reasoning} > \text{memory})_{\text{cond}}$ and $(\text{reasoning} > \text{memory})_{\text{syll}}$. The last two images concerned the integration effect, corresponding to these contrasts on P_2 $(\text{integrable} > \text{nonintegrable})_{\text{cond}}$ and $(\text{integrable} > \text{nonintegrable})_{\text{syll}}$. The four contrast images per subject then underwent a second step comprising two ANOVAs (one for encoding and one for integration) that modeled the mean of each effect. Finally, linear compounds were used to compare these effects, now using between-subject (rather than between-scan) variance. Correction for nonsphericity was used to account for possible differences in error variance across conditions and any nonindependent error terms for repeated measures analysis. The *P*-values corrected for multiple comparisons were assigned using Family Wise Error (FWE) at the voxel-level, considering the whole brain as the volume of interest. Unthresholded *t*-maps are also provided (Supp. Info.) to allow evaluation of the overall distribution of main effect associated brain activity even when changes were not significant.

A conjunction analysis was performed to identify activations common to conditional problems and syllogisms in the integration phase. Conjunction analyses use SPMs of the minimum *t*-statistic compared to a conjunction null [Nichols et al., 2005]. Next, we highlighted areas showing problem-specific responses testing for the interaction between problem type (syllogisms vs. conditionals) and condition (integrable vs. non-integrable). For this interaction, *P*-values corrected for multiple comparisons were computed at cluster level ($P < 0.01$ uncorrected at voxel level).

Finally, as a further exploratory analysis we evaluated whether brain areas that were active during the integration stage of syllogistic reasoning should be considered functionally homogeneous, we ran a principal component analysis (PCA) on the relevant areas. Six regions of interests (ROI) were identified on the basis of the activation map of syllogisms during integration (Fig. 4). The ROIs were processed with the SPM toolbox "marsbar" (http://marsbar.sourceforge.net/- version 0.38.2) to extract the average of the integration effect for syllogistic problems across all voxels for every subject. The PCA was run on SPSS software.

RESULTS

Behavioral Performance

Average accuracy was 75% (SD 16%) for integrable syllogistic problems, and 78% (SD 12%) for integrable conditional problems (Table II). The difference in accuracy between the two types of problem was not significant (paired-$t_{25} = 0.73$; $P > 0.1$). Overall accuracy in nonintegrable problems was 83% (SD 10%) for syllogistic problems, and 86% (SD 11%) for conditional problems. In the subset of nonintegrable problems (on P_2) with a third integrable sentence (P_3), the accuracy was 64% (SD 22%) for syllogistic and 71% (SD 20%) for conditional problems. Thus, performance on problems with three sentences was somewhat poorer than performance on two-sentence integrable problems, but it was still above chance level ($P < 0.001$). This indicates that nonintegrable P2 were also fully processed by subjects.

Response times (Table II) were analyzed by two separate within-subjects ANOVAs. The first was a 2 × 2 ANOVA on the RTs on P_1, the factors being task (reasoning vs. memory) and type of problem (syllogistic vs. conditional problems). The main effect of task was significant [$F(1,25) = 28.67$, $P < 0.001$], with longer RTs in reasoning problems compared to memory problems (Table II). Also, the main effect of problem type was significant [$F(1,25) = 86.05$, $P < 0.001$], with longer RTs to conditional P_1. The interaction was not significant [$F(1,25) < 1$, $P > 0.1$]. The second ANOVA was again a 2 × 2, but on RTs from P_2 trials. Within-subject factors were integrability (integrable vs. nonintegrable premises) and type of problem (syllogistic vs. conditional problems). The main effects of integrability and problem type were both significant [integrability: $F(1,25) = 15.52$, $P < 0.01$; problem type: $F(1,25) = 6.96$, $P < 0.05$], with longer RTs for integrable premises compared to nonintegrable ones, and for syllogisms compared to conditionals (Table II). Given that the interaction was significant [$F(1,25) = 55.99$, $P < 0.001$], we also tested simple main effects, separating conditional from syllogistic problems. The integration effect on RTs was significant for syllogisms (paired-$t_{25} = 6.94$, $P < 0.001$), but not for conditional problems (paired-$t_{25} = 0.32$, $P > 0.1$).

The Heuristic Index (HI) computed on the nonheuristic set was on average 0.43 (SD = 0.17). HI is different from 1 [one-sample $t_{25} = 17.01$, $P < 0.001$], the value expected from a group of subjects always applying the atmosphere heuristic. This result suggests that our paradigm successfully prevented a systematic and generalized application of heuristic strategies to solve quantified problems [Reverberi et al., 2009a].

Neuroimaging Evidence on Encoding and Integration

Two sets of analyses explored the activation associated specifically with different stages of deductive reasoning: the encoding stage and the inference or integration stage.

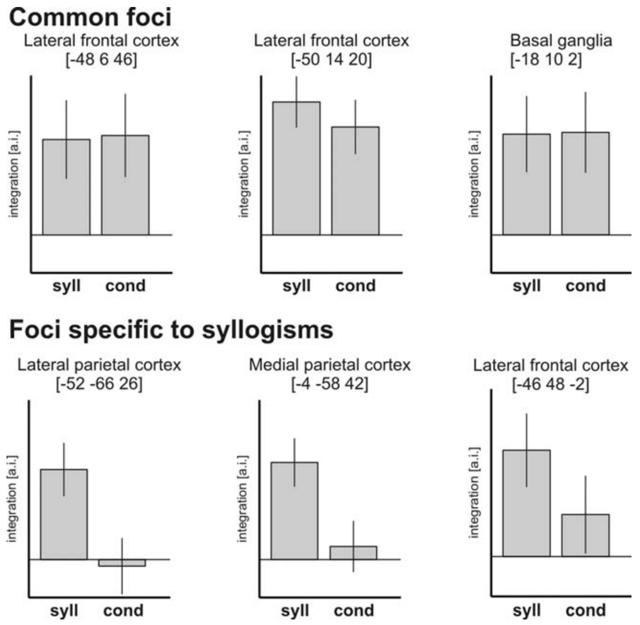

Figure 3.

Parameter estimates for the height of the hemodynamic response related to the integration stage, for conditional (cond) and syllogistic problems (syll). The upper row shows the parameter estimates at the maxima of the conjunction analysis for the integration effect. The lower row shows the parameter estimates at the voxels of maximal difference between conditional and syllogisms for the integration effect (i.e. the problem type × condition interaction in the integration phase). Error bars indicate standard errors.

For the *encoding stage*, we considered brain activity related to the presentation of the first premise (P_1). We compared P_1 in the reasoning task versus P_1 in the memory task (factor "task"), for conditional and syllogistic sentences (factor "type of premise"). No voxels showed more activity during P_1 processing in the reasoning task in conditional or syllogistic sentences. As an additional exploratory analysis, we checked whether greater activity for reasoning versus memory encoding could be detected within the areas that showed a significant integration effect (see below), by applying a small volume correction procedure [SVC, Worsley et al., 1996]. We underline that the encoding effect is independent from the integration effect, thus the use of SVC is valid, not producing a selection bias. The comparison remained nonsignificant for conditional sentences. By contrast, we found that the left lateral frontal lobe was more active during the encoding of syllogistic premises in the reasoning condition with a peak in BA 44/45 ($x, y, z = -56, 28, 20$; $z = 3.73$, $P < 0.05$, corrected). The interaction "problem type (syllogisms vs. conditionals) × task (reasoning vs. memory)" confirmed that the reasoning-related activation during encoding was greater for syllogisms than for conditional premises in BA44/45 ($x, y, z = -58, 20, 26$; $z = 3.48$, $p = 0.07$, corrected).

We investigated the *integration stage* by assessing brain activity associated with the second premise (P_2) of the reasoning task. We first evaluated the integration effect for conditional and syllogistic problems. A reliable simple integration effect, for both conditional and syllogistic problems, was observed in a set of left lateralized frontal brain areas and in left basal ganglia. In particular, integrating premises in both conditional and syllogistic problems produced activation in the left inferior frontal gyrus (Brodmann areas 44/45), the left precentral gyrus (BA 6), the left supplementary motor area (SMA, BA 6), and the left basal ganglia (Table III, Figs. 2 and 3, see also Fig. 1 on Supp. Info. for the unthresholded *t*-maps). In addition, the integration stage with syllogistic problems also activated the left middle frontal gyrus (orbital portion, BA 46), the left precuneus (BA 7), and an area bridging left superior parietal lobule and occipital lobes (BA 19/7). We formally tested whether the integration effect was present and where in both types of problem using a conjunction analysis [Nichols et al., 2005]. This confirmed that the commonly activated brain areas were in the left inferior frontal gyrus, the left precentral gyrus, the left SMA, and left basal ganglia (Table III and Fig. 2, right panel). Next, we assessed the presence of areas showing a difference between the integration effect for syllogisms ($\text{integrable}_{\text{syll}} > \text{nonintegrable}_{\text{syll}}$) and the integration effect for conditionals ($\text{integrable}_{\text{cond}} > \text{nonintegrable}_{\text{cond}}$): i.e. with the interaction problem type (syllogisms vs. conditionals) × condition (integrable vs. nonintegrable). A significant differential effect of integration (with syllogisms > conditionals, Table III) was observed in the occipital medial gyrus, in the lateral parietal lobe (angular gyrus), and precuneus (for all the interaction analyses: $P < 0.05$, corrected for multiple comparisons at cluster level).

Finally, it should be noticed that the integration effect was remarkably lateralized to the left hemisphere, both for conditional and syllogistic problems. Indeed, corresponding regions in the right hemisphere of those robustly activated on the left mostly showed no integration effect whatsoever (see unthresholded *t*-maps in the Supp. Info.). These findings provide evidence for a strong lateralization of the reasoning network to the left hemisphere.

Functional Homogeneity of the Syllogistic Network

Given the extensive fronto-parietal network of brain areas that activated during the integration stage of syllogistic reasoning, we evaluated, as an additional exploratory analysis, whether this network should be considered functionally homogeneous, or whether subtle functional differences could be detected. A possible source of evidence for this issue is the pattern of correlations, across subjects, between each of the identified brain regions. If two or more brain areas are indeed a functional unit, then their activation should correlate highly across subjects.

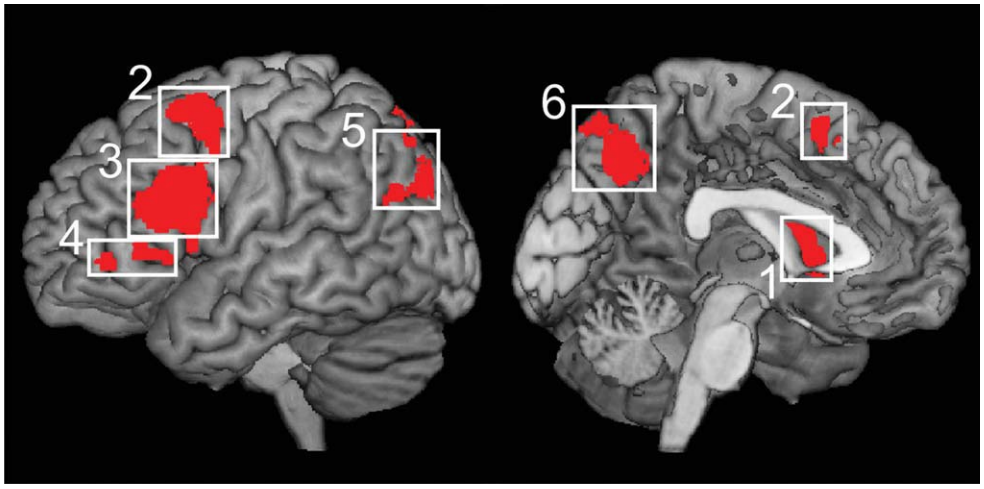

Figure 4.
Regions of interest (ROI) considered for the PCA. These ROIs are based on the areas showing a significant integration effect on syllogistic problems (cf. Fig. 2, left panel). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

That is, a single factor (representing thus "the strength of network activation" in each subject) will capture most of the across-subjects variance in both areas. On the other hand, if the two areas implement different cognitive functions, then their activation pattern will be less correlated. We defined six regions of interests (ROI) on the basis of the activation map of the syllogisms (Fig. 4). Three ROIs were in the frontal lobe: inferior/orbital frontal cortex (BA 46/47, n. 4 in Fig. 4), inferior frontal gyrus (BA 44/45, n. 3), and precentral gyrus/SMA (BA 6, n. 2). Two ROIs were in the parietal lobe (lateral parietal cortex, n. 5; medial parietal cortex, n. 6) and one was in the basal ganglia (n. 1). For each subject, we extracted the average activation in each ROI. Given the relatively large sample of subjects we studied, it was possible to submit the resulting matrix of 26 × 6 values to a principal component analysis. PCA can identify the minimum number of factors required to satisfactorily explain the variance of the original set of variables. It should be noted that the data used in the factor analysis (a matrix of across ROI correlations for the same type of problem - syllogisms) are independent of the data used in the preceding analysis. PCA identified only two components with eigenvalues >1. The first factor accounted for only 60% of the total variance. By introducing the second component, the explained variance rose to 81%. After orthogonal rotation [varimax procedure, Kaiser, 1958], the first component correlated highly with the left inferior frontal gyrus ($r_1 = 0.85$; $r_2 = 0.36$), the inferior frontal/orbital cluster ($r_1 = 0.89$; $r_2 = -0.12$) and precentral gyrus/SMA ($r_1 = 0.70$; 2: $r_2 = 0.58$). By contrast, the second component correlated highly with lateral parietal ($r_1 = 0.09$; $r_2 = 0.92$) and the medial parietal clusters ($r_1 = 0.15$; $r_2 = 0.85$). Intermediate correlation coefficients with both components were found in the basal ganglia ($r_1 = 0.67$; 2: $r_2 = 0.59$). Overall, PCA shows that the network of areas active during integration of quantified sentences is not functionally homogeneous: at least two factors are needed to explain a substantial amount of the variance. The two sets include respectively areas in the frontal lobe and others in the parietal lobe. This result is consistent with the idea that one set of areas is common to conditionals and syllogistic problems (i.e. the frontal regions) and another set is specific to syllogistic problems only (i.e. the parietal regions).

DISCUSSION

Deduction is a basic cognitive ability that allows us to draw conclusions that we deem necessary from pieces of previous knowledge (i.e., premises). Laboratory studies of deduction have used three large classes of problems: relational problems, propositional problems with premises involving logical connectives, and syllogistic problems with premises involving quantifiers. In this study we investigated whether a single reasoning brain network underlies syllogistic and propositional reasoning, or whether these two types of reasoning are associated with different neural networks. Specifically, we compared two types of deductive problem in each of two functional stages of reasoning: namely the encoding of premises and their integration. In the encoding stage, premises are stored in working memory; in the integration stage, they are linked together to generate conclusions.

Encoding of Premises During Conditional and Syllogistic Reasoning

We compared the activation elicited by a statement when the participant knows it will be used for reasoning with the activation elicited by the same statement when it is only to be recognised or remembered. Differences between these two cognitive states may occur because reasoning requires a representation of the meaning of a premise or of its deep logical structure, neither of which are strictly required for literal recall. No difference was found in our whole brain analysis. However, when the analysis was selectively focused on the set of areas activated in the integration phase (see below), we found a significant effect of encoding for reasoning vs. encoding for memory in the left lateral frontal lobe (BA44/45). The effect was present only for syllogistic problems, as also confirmed by the problem type (syllogisms $>$ conditionals) by task (reasoning vs. memory) interaction in this region. Thus, at least in case of syllogisms, encoding for reasoning engages more of the cognitive processes implemented in BA44/45 than encoding for literal recall. The observed activation cannot be explained as a mere effect of longer processing times in the reasoning condition. First, the activation estimates were corrected for the response times at the encoding stage (i.e. activation "per unit time"), so that mere differences in RTs across conditions will not produce differences in the activation estimates. Second, in an analysis of RTs the encoding effect was found with both syllogistic and conditional sentences, but differential activation was only present with syllogisms. One interpretation for this effect in BA44/45 may be related to the extraction and encoding of the logically relevant features of a premise, which would be required for reasoning. However, conditional premises also require the extraction of such features. Why then did BA44/45 not activate for conditional premises too? This may be tentatively explained by the lack of "structural diversity" in the conditional first premises compared to syllogistic premises. All conditional first premises had the general form "if x then y," while in the case of syllogisms three logically relevant elements (all, some, none) had to be differentially encoded and represented. This might have reduced the need for logic-specific processes with conditional encoding. Alternatively, we might speculate that the activation specifically associated with syllogisms during encoding might be due to strategic choices made by subjects. As the integration stage is more demanding for syllogisms than for conditionals, subjects may have decided to fully extract the formal structure of syllogistic sentences on presentation of the first premise to make the following integration stage faster and more efficient. By contrast, in the case of conditional sentences they may have decided to await the presentation of second premises before applying any further logic-specific manipulation.

Overall, our findings show that encoding in syllogistic reasoning recruits cognitive processes over and above those triggered by a memory task using exactly the same stimuli. These processes, arguably support the generation of logic-specific representations and have their neural substrate in BA44/45.

Integration of Premises During Conditional and Quantified Reasoning

In order to identify the integration network in both conditional and quantified problems we contrasted brain activity associated with *integrable* second premises (P_2)—that allow the generation of new deductive conclusions—with brain activity elicited by identical P_2 stimuli that did not permit valid conclusions (*nonintegrable* P_2). We found reliable differences in the brain activation associated with conditional and quantified integrable premises. Both types of problem activated a common set of areas, including left lateral frontal cortex (mainly BA 44/45) and the left basal ganglia (Table III and Fig. 2). Besides those common areas, the integration of syllogistic premises also activated the lateral parietal cortex, the precuneus, and left ventral fronto-lateral cortex. Importantly, our experiment allowed us to check the reliability of these differences within a single and relatively large ($n = 26$) group of subjects by a direct comparison of the integration effect for the two classes of deductive problem. This showed that the parietal areas (lateral parietal cortex and precuneus), which displayed an integration effect for syllogistic problems only, also showed a greater integration effect in syllogisms compared to conditional problems. This result corroborates the hypothesis of the recruitment of differential neural networks for the solution of deductive problems that, while superficially similar, belong to different logical classes.

Furthermore, we assessed whether the set of areas that were more active during syllogistic integration operated as a functionally homogeneous network by means of PCA. If this were the case, a single principal component should explain most of the between-subjects variance. On the contrary, our results show that a combination of two components is necessary to account for about 80% of the between-subjects variance in the syllogistic network, thus highlighting the probable involvement of at least two distinct functional subcomponents. Interestingly, one component included the parietal areas that activated selectively for syllogisms, while the second component included the frontal areas that were similarly activated by the integration of both syllogisms and conditional problems.

Overall, these findings provide converging evidence for the involvement of two discrete sets of brain areas in the integration of deductive premises. The first set includes the left lateral frontal lobe and the basal ganglia. This set is involved both in conditional and syllogistic reasoning and shows a similar level of activity within each subject. These regions implement the set of cognitive processes that is used for the generation of deductive conclusions in both syllogistic and conditional reasoning. The exact nature of these processes varies in the main theories of reasoning. Our study cannot be conclusive in this respect, given the probabilistic nature of the "reverse inferences" [Poldrack, 2006], i.e. the inferences about one particular cognitive function (e.g., syntactic parsing) based on the activation of specific brain regions (e.g. BA 44/45).

Nevertheless, the fact that similar areas in the left lateral frontal cortex and in the basal ganglia have been found in previous studies of abstract conditional rule representation [Bode and Haynes, 2009; Bunge et al., 2003; Muhammad et al., 2006; Seger and Cincotta, 2006] and syntactic manipulation [Ben-Shachar et al., 2004; Dapretto and Bookheimer, 1999; Friederici et al., 2006; Makuuchi et al., 2009] tends to support the mental logic view, which holds that the detection of formal structures in premises automatically triggers basic, valid, rule-like inferential schemata.

Our findings are compatible with several previous studies on the neural bases of propositional and syllogistic reasoning. Activation of BA 44/45 is almost invariably observed and the activation of BA 6 and the basal ganglia have also been often reported [though somewhat less consistently, see Goel et al., 2000; Goel and Dolan, 2003; Goel and Dolan, 2004; Reverberi et al., 2007; Rodriguez-Moreno and Hirsch, 2009]. However, the activation of BA44/45 is at odds with two previous imaging studies, one on the neural basis of propositional reasoning [Monti et al., 2007; see also Noveck et al., 2004, but notice that the latter study may have missed some critical reasoning processes given the time window of analysis considered] and the other of syllogistic reasoning [Rodriguez-Moreno and Hirsch, 2009]. Monti and collaborators compared brain activation while subjects solved complex propositional problems (e.g. modus tollens) versus simple propositional problems (e.g. modus ponens). The results showed "reasoning load" effects in a wide network of areas, including BA10, BA8, and BA 47, but not BA44/45. On the other hand, Rodriguez-Moreno and Hirsch [2009] compared brain activation during syllogistic reasoning versus a memory task. They found activation in frontal areas (e.g. BA6, BA8, BA9, BA10, BA47) and parietal areas (BA 40, BA7), but again not in BA44/45. Several differences in the experimental paradigms and stimuli may explain the partial discrepancies between those studies and ours. First, Monti and collaborators' subjects were asked to *evaluate* the validity of proposed conclusions in deductive problems. The cognitive processes involved in the evaluation of a conclusion may well differ from those needed for the generation of a conclusion. Second, the propositional problems used by Monti were more complex than those we employed. Complex propositional problems may require qualitatively different reasoning systems than those needed to solve simpler problems. This explanation is consistent with the theoretical predictions of Mental Logic theory, which postulate a qualitative transition between the processes involved in the solution of modus ponens, as compared to modus tollens problems [Braine and O'Brien, 1998; Reverberi et al., 2009b].

However, neither the first nor the second interpretation applies to the study of Rodriguez-Moreno and Hirsch [2009], who used stimuli (syllogisms with semantic content) and experimental procedures (separation between generation and evaluation) very similar to those we employed. Both Monti and collaborators and Rodriguez-Moreno and Hirsch administered the deductive problems at a relative slow pace (in Monti et al., the time from presentation to solution ranged between 8 and 15 s; in Rodriguez-Moreno and Hirsch's study subjects, having seen two premises waited 18 s before answering, or made responses 10 s after being presented conclusions). In our study, subjects generated deductive conclusions within 3.3 (conditional) or 4 s (syllogisms) of the second premise. Thus, in our paradigm, the generation of deductive conclusions was closely "time-locked" to the presentation of the second premise. This difference in design may have caused a differential sensitivity to "sustained" vs. "transient" reasoning mechanisms, as previously suggested for other cognitive control functions [Braver et al., 2003]. Accordingly, we hypothesize that BA 44/45 activates in a transient manner during the generation of conclusions, and that previous studies may have missed this because they emphasized sustained processes instead [Monti et al., 2007; Rodriguez-Moreno and Hirsch, 2009]. Additional studies with specific fMRI protocols that enable separation of "sustained" versus "transient" activations are warranted to test this proposal.

Overall, our findings restate the role of the left lateral frontal lobe and basal ganglia in deductive reasoning, but in a way that is more specific both from a cognitive perspective because they pertain exclusively to the integration stage, and from an anatomo-functional perspective, because in previous studies activated areas were usually embedded in more widespread networks.

The set of areas that activated during integration includes the lateral parietal cortex and the precuneus. These regions activated selectively during syllogistic reasoning and dissociated from the frontal areas in a principal component analysis of interregional correlations. Together, these findings indicate that the integration of syllogistic premises recruits processes that are not engaged by conditional reasoning. Our results do not fit with the hypothesis that the same cognitive mechanisms underlie both syllogistic and conditional reasoning. However, they are in agreement with many previous studies on syllogistic reasoning [e.g., Bacon et al., 2003; Ford, 1995; Störring, 1908], which have shown variability in peoples' self reports about the specific strategies they use to integrate premises in different syllogistic problems. Conditional reasoning typically does not involve such a variety of strategies. This difference may suggest that conditional reasoning is carried out by means of a single set of processes, implemented in the left lateral cortex and the basal ganglia. On the other hand, syllogistic reasoning, which may result from a plurality of strategies, recruits a wider range of cognitive processes. Their contribution is reflected in the additional activation of parietal and ventro-lateral frontal areas that we find. Consistently, the network of areas engaged by integration of syllogisms is compatible with the alternative cognitive processes assumed by Mental Model and Mental Logic theories. As noted earlier, activation of BA 44/45 can be associated with rule-guided transformations. On the other hand, activation of the superior parietal cortex (BA 7) has also been related to the representation and manipulation of spatial relations among terms [Cavanna and Trimble, 2006]. These processes are reminiscent of the cognitive operations that the Mental Model theory proposes are involved during deductive inference.

An alternative explanation for the recruitment of additional areas during syllogistic deduction capitalise on the fact that the administered syllogisms proved to be more demanding to solve than the conditional problems, as indexed by the longer reaction times (Table II). This leaves open the possibility that any complex reasoning procedure, even those not involving quantified sentences, would nevertheless additionally activate inferior lateral frontal cortex and the parietal lobe. This would prompt to reinterpret the dissociation reported here as an instance of a dissociation between complex and easy deductive reasoning. The hypothesis needs to be formally tested.

Reliability of the Experimental Paradigm

Recently, three main criticisms have been raised about neuroimaging studies of deductive reasoning. First, it has been claimed that baseline tasks in previous experimental paradigms were not processed at the same level as experimental conditions [Monti et al., 2007]. An incomplete or superficial processing at baseline may have contributed to the involvement of linguistic areas in deductive reasoning observed in many studies [e.g. Goel et al., 2000; Goel and Dolan, 2003]. Here, we dealt with this issue by inducing subjects to pay as much attention to integrable second premise as to nonintegrable ones. In some trials, nonintegrable P_2 premises had to be integrated with a third premise (P_3), therefore discouraging shallow processing at P_2. Superficial processing of P_2 would have resulted in random performance on deductive problems that included the third premise (P_3), which was not the case. Furthermore, our design also provides an equalization of working memory requirements for both integrable and nonintegrable premises with P_2. A working memory "refresh" (i.e., a change in working memory content) takes place for both integrable (encoding of the new conclusion) and nonintegrable premises (encoding of a completely new stimulus, P_2), while overall memory load is kept constant. The good match of integrable and nonintegrable statements is also empirically corroborated by the fact that the processing time of conditional problems between the two tasks was not distinguishable (Table II). Notwithstanding the higher mnestic and linguistic processing requirements at baseline, BA 44/45 was activated similarly to preceding studies. Therefore, activation of BA 44/45 cannot be accounted for by inadequately controlled baseline stimuli. On the other side, the use of an improved baseline might be the cause of the lack of the activation in the left parietal lobule (BA40) for conditional problems, which was observed in our preceding study on propositional reasoning[4] [Reverberi et al., 2007].

A second criticism is that in previous studies involving syllogistic reasoning [Goel et al., 2000; Goel and Dolan, 2003] subjects may have solved most problems by means of a simple, logically invalid heuristic: e.g. the "atmosphere" heuristic [Beggs and Denny, 1969; Chapman and Chapman, 1959; Reverberi et al., 2009a; Woodworth and Sells, 1935]. In a behavioral study, Reverberi et al. [2009a] provided evidence that indeed the vast majority of their participants (>90%) used heuristic strategies when performing reasoning tasks similar to those used by Goel et al. [2000, 2003, 2004]. This was probably because of the strict time constraints imposed for solution assessment and because of the exclusive use of syllogisms that could be solved correctly using heuristic strategies. These findings raise some doubts about the interpretation of previous neuroimaging findings of syllogistic reasoning. Here, we addressed this issue by making the use of heuristics inconvenient. Thus, we relaxed time constraints and introduced a set of problems for which the atmosphere heuristic leads to the wrong conclusion. This set was inserted both in the preexperimental training session and in the fMRI experiment. Thus, during training subjects realized that simple heuristics failed to work correctly for all problems (feed-back provided after each trial). During fMRI, half the syllogisms were not correctly solvable with an atmosphere heuristic approach. In this way, we prevented a systematic and generalized application of heuristic strategies to solve quantified problems. Our finding suggests that, despite these procedures, our activations associated with syllogistic reasoning partially overlap with those reported by Goel et al. [2000] suggests that formal heuristic (as atmosphere heuristic) and valid analytical strategies involve similar brain areas.

A third recent criticism has been addressed to a preceding study by our group on propositional reasoning [Reverberi et al., 2007]. Monti et al. [2009] have pointed out that simple deductive inferences, such as modus ponens, might be solved by means of pattern matching routines rather than "true" deductive reasoning processes. They further underline that this would particularly be the case when training is administered before MRI scanning. Both theoretical and empirical considerations might be raised here. Empirically, it is unlikely that in our preceding study the training procedure has introduced a systematic change on how the subjects solve deductive problems. If this was true then we should have observed behavioural (during training or scanning) or brain activation changes in relation to practice. However both behavior and brain activations were stable throughout the experiment [see Fig. 2 in Supp. Info. and Reverberi et al., 2007]. Furthermore, in the present experiment, we used a definitively larger set of

---

[4] A further difference with the preceding study by our group is the use of double conditional problems instead of modus ponens. However double conditionals should not involve different cognitive processes than modus ponens [Santamaria et al., 1998].

inferences (18 overall, three for conditionals and 15 for syllogisms), for which it would have been difficult and inconvenient to create a full set of pattern matching rules. Yet, we were able to replicate the frontal activations obtained in the preceding study. Overall, the available evidence points towards both a "cognitive neutrality" of training, at least for simple deductive problem already well practiced in daily life, and an involvement of BA 44/45 also when pattern matching is not a viable option.

From the theoretical point of view, one may ask what should be considered "true" deductive reasoning and what should not. One definition considers an argument as "deductive" whenever the premises provide a full guarantee about the truth of the conclusion. Following from this definition, we can assume that a subject is reasoning deductively whenever he tries to generate a certainly true conclusion given the premises. The range of difficulty in correctly doing so varies widely. At the easy end, all scholars in the field agree that even the extremely simple "modus ponens" involves deductive reasoning (If A then B; A; therefore, B). Besides modus ponens, several other very simple inferences are considered to trigger deductive reasoning. According to Mental Logic theories, some inferences are very easy because individuals innately have—or soon acquire—the ability to recognize and apply some truth-preserving inferential patterns: "many psychologists believe that children learn to reason by acquiring an internal system of logic [...]. Reasoning is thus an essentially syntactic or pattern-matching process in which formal rules are applied to the premises regardless of their meaning. Indeed, the power of a formal calculus resides in the feasibility of this application." [Johnson-Laird et al., 1986]. What makes "deductive" such a pattern recognition procedure is the type of patterns recognized ("if A then B"; "A") and the actions they trigger ("B"), i.e. whether the patterns recognized/applied are or are not valid, truth-preserving deductive arguments.

Thus, two interesting empirical question emerges from this way of framing current research on deduction. First, is there a qualitative difference between simple deductive reasoning—amenable to be solved by pattern matching—and more complex reasoning [Reverberi et al., 2009b]? In case of positive answer then it should be important to explore the neural basis of both type of deductions: the simple ones, and the more complex ones, possibly associated with higher intellectual abilities. Second, is there any difference from the (neuro)cognitive point of view between deductively valid "pattern recognition" and deductively invalid "pattern recognition" (e.g. formal heuristics, or fallacies like the "affirmation of the consequent" "if A then B," "B," "therefore A")? Further studies are warranted to directly answer these fundamental questions.

CONCLUSIONS

Our study complements and further specifies previous neuroimaging findings concerning deductive arguments, including conditional arguments and categorical syllogisms. We investigated two stages of reasoning, namely the encoding of premises and their subsequent integration.

Encoding syllogistic premises for reasoning activates BA 44/45 more than encoding for literal recall. By contrast, encoding of a conditional premise for reasoning does not recruit any other areas compared to encoding for literal recall. This shows that, at least for the case of syllogisms, additional cognitive processes are recruited to support the generation of logic-specific representations.

The integration of conditional premises activates left lateral frontal cortex (mainly BA 44/45) and basal ganglia. Integration of syllogistic premises activates the same fronto-striatal network plus additional regions in the left lateral parietal, medial parietal and left ventro-lateral frontal cortex. Thus, at the integration stage, syllogistic arguments recruit an additional set of areas than do conditional arguments. These findings challenge the view that a single reasoning system underlies both types of arguments, rather they support cognitive theories and empirical studies which suggest that syllogistic reasoning involves qualitatively different cognitive processes.

Finally, the activation of BA 44/45 during both encoding (syllogisms) and premise integration (syllogisms and conditionals) suggests a central role for syntactic manipulations and formal/linguistic representations during deductive reasoning.

ACKNOWLEDGMENTS

We thank Patrice Rusconi for having collected data for the behavioral pilot study and two anonymous referees for the useful comments. The Neuroimaging Laboratory of the Santa Lucia Foundation is supported by the Italian Ministry of Health.

REFERENCES

Bacon AM, Handley SJ, Newstead SE (2003): Individual differences in strategies for syllogistic reasoning. Think Reason 9:133–161.

Beggs I, Denny JP (1969): Empirical reconciliation of atmosphere and conversion interpretations of syllogistic reasoning errors. J Exp Psychol 81:351–354.

Ben-Shachar M, Palti D, Grodzinsky Y (2004): Neural correlates of syntactic movement: Converging evidence from two fMRI experiments. NeuroImage 21:1320.

Bode S, Haynes JD (2009): Decoding sequential stages of task preparation in the human brain. Neuroimage 45:606–613.

Braine MDS, O'Brien DP, editors (1998): Mental Logic. Mahwah, NJ: Lawrence Erlbaum Associates. 481 p.

Braver TS, Reynolds JR, Donaldson DI (2003): Neural mechanisms of transient and sustained cognitive control during task switching. Neuron 39:713–726.

Bunge SA, Kahn I, Wallis JD, Miller EK, Wagner AD (2003): Neural circuits subserving the retrieval and maintenance of abstract rules. J Neurophysiol 90:3419–3428.

Byrne RMJ, Johnson-Laird PN (2009): 'If' and the problems of conditional reasoning. Trends Cogn Sci 13:282–287.

Cavanna AE, Trimble MR (2006): The precuneus: A review of its functional anatomy and behavioural correlates. Brain 129:564–583.

Chapman LJ, Chapman JP (1959): Atmosphere effect re-examined. J Exp Psychol 58:220–226.

Clark HH (1969): Influence of language on solving three-term series problems. J Exp Psychol 82:205–215.

Dapretto M, Bookheimer SY (1999): Form and content: Dissociating syntax and semantics in sentence comprehension. Neuron 24:427–432.

De Soto CB, London M, Handel S (1965): Social reasoning and spatial paralogic. J Pers Soc Psychol 2:513–521.

Dickstein LS (1978): The effect of figure on syllogistic reasoning. Mem Cogn 6:76–83.

Erickson JR (1974): A set analysis theory of behavior in formal syllogistic reasoning tasks. In: Solso R, editor. Loyola Symposium on Cognition. Hillsdale, NJ: Erlbaum. pp 305–329.

Evans JSBT, Handley SJ, Over DE (2003): Conditionals and conditional probability. J Exp Psychol: Learn Mem Cogn 29:321–335.

Fangmeier T, Knauff M, Ruff CC, Sloutsky V (2006): FMRI evidence for a three-stage model of deductive reasoning. J Cogn Neurosci 18:320–334.

Ford M (1995): Two modes of mental representation and problem solution in syllogistic reasoning. Cognition 54:1–71.

Friederici AD, Fiebach CJ, Schlesewsky M, Bornkessel ID, von Cramon DY (2006): Processing linguistic complexity and grammaticality in the left frontal cortex. Cereb Cortex 16:1709–1717.

Friston KJ, Holmes AP, Price CJ, Buchel C, Worsley KJ (1999): Multisubject fMRI studies and conjunction analyses. Neuroimage 10:385–396.

Friston KJ, Glaser DE, Henson RN, Kiebel S, Phillips C, Ashburner J (2002): Classical and Bayesian inference in neuroimaging: Applications. Neuroimage 16:484–512.

Goel V, Dolan RJ (2001): Functional neuroanatomy of three-term relational reasoning. Neuropsychologia 39:901–909.

Goel V, Dolan RJ (2003): Explaining modulation of reasoning by belief. Cognition 87:B11–B22.

Goel V, Dolan RJ (2004): Differential involvement of left prefrontal cortex in inductive and deductive reasoning. Cognition 93:B109–B121.

Goel V, Buchel C, Frith C, Dolan RJ (2000): Dissociation of mechanisms underlying syllogistic reasoning. Neuroimage 12:504–514.

Goel V, Makale M, Grafman J (2004): The hippocampal system mediates logical reasoning about familiar spatial environments. J Cogn Neurosci 16:654–664.

Goodwin GP, Johnson-Laird PN (2005): Reasoning about relations. Psychol Rev 112:468–493.

Hagert G (1984): Modeling mental models: Experiments in cognitive modeling of spatial reasoning. In: O'shea T, editor. Advances in Artificial Intelligence: Proceedings of the Sixth European Conference on Artificial Intelligence. Amsterdam: North-Holland. pp 389–398.

Jager R (1972): The Development of Bertrand Russell's Philosophy. London: Allen & Unwin.

Johnson-Laird PN, Byrne RMJ (1991): Deduction. Hillsdale, NJ, England: Lawrence Erlbaum Associates. 243 p.

Johnson-Laird PN, Oakhill J, Bull D (1986): Children's syllogistic reasoning. Q J Exp Psychol 38A:35–58.

Kaiser HF (1958): The varimax criterion for analytic rotation in factor analysis. Psychometrika 23:187–200.

Knauff M, Fangmeier T, Ruff CC, Johnson-Laird PN (2003): Reasoning, models, and images: Behavioral measures and cortical activity. J Cogn Neurosci 15:559–573.

Makuuchi M, Bahlmann J, Anwander A, Friederici AD (2009): Segregating the core computational faculty of human language from working memory. Proc Natl Acad Sci USA 106:8362–8367.

Monti MM, Osherson DN, Martinez MJ, Parsons LM (2007): Functional neuroanatomy of deductive inference: A language-independent distributed network. Neuroimage 37:1005–1016.

Monti MM, Parsons LM, Osherson DN (2009): The boundaries of language and thought in deductive inference. Proc Natl Acad Sci USA 106:12554–12559.

Muhammad R, Wallis JD, Miller EK (2006): A comparison of abstract rules in the prefrontal cortex, premotor cortex, inferior temporal cortex, and striatum. J Cogn Neurosci 18:974–989.

Nichols T, Brett M, Andersson J, Wager T, Poline JB (2005): Valid conjunction inference with the minimum statistic. Neuroimage 25:653–660.

Noveck IA, Goel V, Smith KW (2004): The neural basis of conditional reasoning with arbitrary content. Cortex 40:613–622.

Oaksford M, Chater N (1994): A rational analysis of the selection task as optimal data selection. Psychol Rev 101:608–631.

Oaksford M, Chater N (2003): Optimal data selection: Revision, review, and reevaluation. Psychom Bull Rev 10:289–318.

Ohlsson S (1984): Induced strategy shifts in spatial reasoning. Acta Psychol (Amst) 57:47–67.

Penny WD, Holmes AP, Friston KJ.2004. Random-effects analysis. In: Frackowiak RSJ, Friston KJ, Frith C, Dolan R, Price C, Zeki S, Penny WD, editors. Human Brain Function, 2nd ed. San Diego (CA): Academic Press. pp 843–850.

Poldrack RA (2006): Can cognitive processes be inferred from neuroimaging data? Trends Cogn Sci 10:59.

Politzer G, Van der Henst J-B, Luche CD, Noveck IA (2006): The interpretation of classically quantified sentences: A set-theoretic approach. Cogn Sci 30:691–723.

Reverberi C, Cherubini P, Rapisarda A, Rigamonti E, Caltagirone C, Frackowiak RS, Macaluso E, Paulesu E (2007): Neural basis of generation of conclusions in elementary deduction. Neuroimage 38:752–762.

Reverberi C, Rusconi P, Paulesu E, Cherubini P. (2009a) Response demands and the recruitment of heuristic strategies in syllogistic reasoning. Q J Exp Psychol (Colchester) 62:513–530.

Reverberi C, Shallice T, D'Agostini S, Skrap M, Bonatti LL (2009b) Cortical bases of elementary deductive reasoning: Inference, memory, and metadeduction. Neuropsychologia 47:1107–1116.

Rips LJ (1994): The Psychology of Proof: Deductive Reasoning in Human Thinking. Cambridge, MA, US: The MIT Press. xiii, 449 p.

Roberts MJ (2004): Heuristics and reasoning I: Making deduction simple. In: Leighton JP, Sternberg RJ, editors. The Nature of Reasoning. New York, NY: Cambridge University Press. 470 p.

Rodriguez-Moreno D, Hirsch J (2009): The dynamics of deductive reasoning: An fMRI investigation. Neuropsychologia 47:949–961.

Santamaria C, Garcia-Madruga JA, Johnson-Laird PN (1998): Reasoning from double conditionals: The effects of logical structure and believability. Think Reason 4:97–122.

Seger CA, Cincotta CM (2006): Dynamics of frontal, striatal, and hippocampal systems during rule learning. Cereb Cortex 16:1546–1555.

Stenning K, Monaghan P (2004): Strategies and Knowledge Representation. In: Leighton JP, Sternberg RJ, editors. The Nature of Reasoning. New York, NY, US: Cambridge University Press. pp 129–168.

Stenning K, Oberlander J (1995): A cognitive theory of graphical and linguistic reasoning: Logic and implementation. Cogn Sci 19:97–140.

Störring G (1908): Experimentelle Untersuchungen über einfache Schlussprozess. Archiv für die gesamte Psychologi 11:1–27.

Woods M, Wiggins D, Edgington D (1997): Conditionals. Oxford, UK: Oxford University Press.

Woodworth RS, Sells SB (1935): An atmosphere effect in syllogistic reasoning. J Exp Psychol 18:451–460.

Worsley KJ, Marrett S, Neelin P, Vandal AC, Friston KJ, Evans AC (1996): A unified statistical approach for determining significant signals in images of cerebral activation. Hum Brain Mapp 4:58–73.