Recomposing a fragmented literature: How conditional and relational arguments engage different neural systems for deductive reasoning

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ABSTRACT

Deductive reasoning is traditionally viewed as a unitary process involving either rule-based or visuo-spatial mechanisms. However, there is a disagreement in the neuroimaging literature on whether the data support one alternative over the other. Here we test the hypothesis that discrepancies in the literature result from the reasoning materials themselves. Using functional magnetic resonance imaging, we measure brain activity of participants while they integrate the premises of conditional arguments (primarily Modus Tollens: If P then Q; not-Q) and Relational Syllogisms (i.e., linear arguments of the sort P is to the left of Q; Q is to the left of R). We find that reasoning with Modus Tollens activates the left inferior frontal gyrus to a greater extent than the Relational Syllogisms. In contrast, the Relational Syllogisms engage the right temporo-parieto-occipital junction more than conditional arguments. This suggests that conditional reasoning relies more on so-called syntactic processes than relational reasoning, while relational reasoning may rely on visuo-spatial processes and mental imagery more than conditional reasoning. This investigative approach, together with its results, clarifies some apparently inconsistent findings in this literature by showing that the nature of the logical argument, whether it is relational or conditional, determines which neural system is engaged.

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Introduction

The ability to draw valid conclusions from prior information is central to human thinking and the endeavor of explaining how participants do so is at the very heart of the reasoning literature. Therefore, there has been considerable interest in the basic cognitive processes underlying standard reasoning tasks that concern conditional arguments such as Modus Ponens (MP) in (1) and Modus Tollens (MT) in (2), or Relational Syllogisms (RS), which can be seen in (3).[1]

(1) If there is a circle then there is a triangle.
   There is a circle.
   Therefore, there is a triangle.
(2) If there is a circle then there is a triangle.
   There is not a triangle.
   Therefore, there is not a circle.
(3) The circle is to the left of the triangle.
   The triangle is to the left of the square.
   Therefore, the circle is to the left of the square.

Central to the investigation of these standard forms of reasoning is a long standing debate on the nature of the mental representations that they call upon. On the one hand, it has been argued that deduction resembles, to a limited extent, rules of inference akin to those of a logical calculus. This account, which harks back to the Mental Logic Theory (MLT) and is often referred to as a syntactic account, posits that reasoners apply rules to a propositional representation of the premises (Braine and O'Brien, 1998; Rips, 1994). In (1) for example, the rule [If P then Q and P; therefore Q] would be applied to the major premise *If there is circle then there is a triangle* and the minor premise *There is a circle* to infer the conclusion *There is a triangle*. Similarly, understanding more complex MT arguments such as the one in (2) would require the application of a complex chain of deductions involving, among other things, *reductio ad absurdum* (e.g., If *circle* were true, then *triangle* would have to be true, but triangle is false, so circle must be false). In principle, one can extend the Mental Logic approach to spatial rules as well. This can be found in Hagert's A.I. model (Hagert, 1984).[2] That is, the premises *The circle is to the left of the triangle* and *The triangle is to the left of the square* can be represented as [Left(X,Y) and Left(Y,Z); therefore Left(X,Z)] to derive the conclusion *The circle is to the left of the square* in (3). Some have assumed that, given the MLT's account of fundamental inference

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[1] Although the relational arguments investigated in the present experiment are based only on the spatial relations *to the left of* and *to the right of*, relational arguments can involve non-spatial relations as well (e.g., *younger than, faster than, before*) (Schaeken et al., 1996).

[2] Although the mention of Hagert (1984) is typically found in the work of Byrne and Johnson-Laird (1989) and Johnson-Laird (1994), Mental Logicians have never developed such a genuine model of spatial reasoning (though Rips seems to advocate that such a model exists; Rips, 1994 pp. 414–415 note 3; see also, Van der Henst, 2002).

making, all logical inference making ought to be supported by the brain region that is central to syntax processing in language, i.e., the left inferior frontal gyrus (IFG) (Goel et al., 2000; Noveck et al., 2004).[3]

On the other hand, it has been proposed that deduction does not rely on rule-based processes but rather visuo-spatial mechanisms. According to this account, known as the Mental Model Theory (MMT), a putative conclusion is generated based on a representation of the premises that takes the form of a mental model whose structure is analogous to the structure of the situation described by the premises (Johnson-Laird, 1983, 2001, 2006; Johnson-Laird and Byrne, 1991). Reasoners then validate this conclusion by ensuring that the constructed mental model is not falsified by alternatives. The applicability of this approach is more apparent with relational reasoning, which is why we first discuss the example in (3). To be more specific, the MMT proposes that the first premise in (3) (i.e., *The circle is to the left of the triangle*) is represented by the following mental models:

○ Δ

When faced with the second premise *The triangle is to the left of the square*, reasoners would find the triangle in the array above and insert a square in the appropriate place (Byrne and Johnson-Laird, 1989):

○ Δ □

The conclusion *The circle is to the left of the square* can then be derived from the scanning of this spatial representation.

The Mental Models approach can be extended to conditional reasoning. In this case, the major premise *If there is a circle then there is a triangle* from (1) and (2) would, at least initially, be represented by the mental model below:

○ Δ
...

where the first line depicts an explicit mental model and where the ellipsis represents potential implicit mental models (i.e., alternative models compatible with the premises). In (1), when the minor premise *There is a circle* is presented, reasoners can immediately eliminate the implicit mental models and endorse the conclusion *There is a triangle* from the explicit mental model. In (2), the premise *There is not a triangle* prompts the reasoner to render explicit models that are otherwise implicit, i.e., to flesh out the implicit model as shown below:

○   Δ
¬ ○   Δ
¬ ○ ¬ Δ

where ¬ represents a negation. Because the minor premise *There is not a triangle* is only compatible with the last model, reasoners ultimately eliminate each of the first two models and accept the conclusion *There is not a circle* as new information that can be drawn out of the last model. Given its visuo-spatial nature, the MMT predicts that deductive reasoning does not engage regions involved in syntax or rule-based processing, but instead relies on brain areas typically involved in mental imagery and visuo-spatial processing, i.e., regions of the parieto-occipital cortex (Goel and Dolan, 2001; Johnson-Laird, 1994; Noveck et al., 2004).

Although deductive reasoning has been the focus of an increasing amount of neuroimaging research over the past decade, there is still lack of agreement on whether the data show that it relies on rule-based or visuo-spatial neural mechanisms (Goel, 2007). For example,

Noveck et al. (2004) investigated the neural correlates of abstract conditional arguments, such as MP and MT in (1) and (2). The authors found that endorsing the conclusion of conditional inferences engages both the left parietal cortex (for MP arguments) and the left IFG (for MT arguments). Reverberi et al. (2007) further showed that the left IFG and the left inferior parietal cortex are involved specifically in integrating the premises of a chain of conditional arguments (see also Reverberi et al., in press, for a confirmation of the role of the left IFG in integrating the premises of conditional arguments). Overall, the activation of the left IFG during conditional reasoning appears to support a syntactic or rule-based view of deductive reasoning, in line with the MLT.

However, others have reported deduction-related activations outside of the neural system predicted by the MLT. Goel and Dolan (2001), for instance, found that endorsing the conclusion of an abstract three-term RS such as the one in (3) elicits activations in bilateral parietal and occipital cortices, but not in the left IFG or in the regions that have been recently associated with rule-based processing (the left rostrolateral prefrontal cortex, RLPFC, and medial superior frontal gyrus, mSFG; Monti et al., 2009). This result, replicated since by several other studies (Acuna et al., 2002; Fangmeier and Knauff, 2009; Fangmeier et al., 2006; Goel et al., 2004; Heckers et al., 2004; Knauff et al., 2003), provides some support for a visuo-spatial account of deductive reasoning such as the MMT.

Both the MLT and the MMT have been largely interpreted as "unitary" models of reasoning in the neuroimaging literature (Goel, 2007). However, this unitary approach is undermined when a set of fundamental reasoning tasks activate different constellations of brain regions. It is thus reasonable to assume that deduction involves heterogeneous processes. This has been suggested by the Mental Logic theorists themselves (Braine and O'Brien, 1998, p.194) so such a "hybrid" approach is not unheard of. Johnson-Laird and colleagues have considered this as well (Ehrlich and Johnson-Laird, 1982; Mani and Johnson-Laird, 1982) and it has been proposed more recently by Van der Henst and Schaeken (2005), in the wake of Mental Logic–Mental Models debates. In fact, for some time, many have proposed that syntactic and visuo-spatial processes are modulated differentially by a number of variables such as the degree of imagery raised by the premises (Ormrod, 1979; Shaver et al., 1975; Williams, 1979), the presentation mode (simultaneous vs. sequential, see Ormrod, 1979; Van der Henst and Schaeken, 2005), the indeterminacy of the premises (Fleming et al., submitted for publication; Mani and Johnson-Laird, 1982) and individual differences (Ford, 1995; Galotti et al., 1986; Roberts, 2000; Shaver et al., 1975; Van der Henst and Schaeken, 2005).

Therefore, it is possible that the engagement of rule-based (or syntactic) mechanisms in reasoning depends upon the deductive task. This hypothesis is suggested by behavioral studies showing that rates of correct performance in a conditional reasoning task are correlated with measures of verbal, but not visuo-spatial, working memory (Handley et al., 2002). Conversely, rates of correct performance in a relational reasoning task are affected by taxing the visuo-spatial, but not the verbal, working-memory resources (Vandierendonck and De Vooght, 1997). Conditional and relational reasoning may thus preferentially recruit linguistic and visuo-spatial mechanisms, respectively.

The goal of the present functional magnetic resonance imaging (fMRI) experiment was to address in detail the following issue. While a unitary view of the MLT would predict the engagement of regions associated with syntax and rule-based processing (i.e., the left IFG according to Goel, 2007, or perhaps the left RLPFC and mSFG according to Monti et al., 2009) in both conditional and relational arguments, a hybrid view of reasoning would anticipate differential involvement of these regions depending on the deductive argument. Specifically, based on previous research (Acuna et al., 2002; Goel and Dolan, 2001; Handley et al., 2002; Noveck et al., 2004; Reverberi et al., in press; Reverberi et al., 2007; Vandierendonck and De Vooght, 1997), we

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[3] Others have recently argued that the MLT would also be consistent with activation of regions associated with rule representation and goal/subgoal processing, such as the left rostrolateral prefrontal cortex (RLPFC) and the medial superior frontal gyrus (mSFG) (Monti et al., 2007, 2009).

predict that the linguistic mechanisms of the left IFG will be engaged more in conditional rather than in relational arguments. We further anticipate that relational arguments will recruit the visuo-spatial mechanisms of the parieto-occipital cortex to a greater extent than conditional arguments.

This is why we compare the neural activity associated with conditional and relational arguments. As materials, we employed the two standard conditional arguments described above (MP and MT) and spatial RS involving the relations *to the left of* and *to the right of*. We adopt a technique, introduced first by Reverberi et al. (2007), which captures activity at the moment two premises are *integrated* (as opposed to capturing activity at the moment a conclusion is evaluated). We do so because, as noted elsewhere (Bonnefond and Van der Henst, 2009; Reverberi et al., in press; Reverberi et al., 2007), the neural activity associated with premise integration arguably provides better insight into the process of *generating* a deduction (for a discussion on this topic, see Reverberi et al., 2007).

It should be noted that this experimental approach relies on comparing integrable to non-integrable arguments. Within the neuro-imaging literature, *integrable* refers to cases where two premises (such as those in (1)–(3)) can provide a deductive conclusion and *non-integrable* refers to cases where two pieces of information cannot be connected to one another. For example, consider the case of two, non-integrable premises below:

If there is a square then there is a circle.
There is a triangle.

Trials using non-integration have been common in neuroimaging experiments, especially when it is presented as part of a conclusion (Goel et al., 2000; Goel and Dolan, 2001, 2003; Qiu et al., 2007). Consider for example this trial taken from Goel and Dolan (2001):

Nancy is younger than Karen, Karen is younger than Jake.
Therefore Mary is richer than Jane.

The non-integrable premises are designed to be controls because they do not license inferencing. In the Reverberi et al. (2007) experiment, for example, the authors presented a series of arguments containing three lines (e.g., *P; If P then Q; If Q then R*) and they measured brain activity at the moment that the conditional premise arose. The non-integrable premises (e.g., the second premise in *P; If Q then R; If P then S*) served as useful controls since they were propositions that cannot be integrated and be sources of inferencing.

We point out how this technique works because it is not clear that non-integrable premises always serve as ideal controls. This should not be surprising because the neuroimaging literature on reasoning has long recognized that control items are rarely completely satisfactory (Bonnefond and Van der Henst, 2009; Noveck et al., 2004). For example, Bonnefond and Van der Henst (2009) observed that the processing of non-integrable premises result in an N2 electrophysiological compo-nent, which is typically observed when expectations are violated or when a cognitive conflict is experienced. This is an indication that non-integrable premises are not simply ignored but are rather potential sources of dashed expectations, which is not what one is after.

Arguably, the non-integrable sentences in Reverberi et al.'s (2007) case are effective since its three-premise design used two of the more fundamental propositional logical inferences (*if–then* and *or*) and often provided participants with the luxury of bypassing premises (e.g., in order to anticipate information later on).[4] The current study, which includes more complex forms and thus only two premises per trial, is cognizant of the persistent challenge that non-integrable premises represent and we will thus pay careful attention to these

controls throughout. Specifically, we will assess the amount of effort required by non-integrable premises by analyzing their reading time and we will apply an exclusion criterion: In cases where non-integrable premises turn out to require a significantly longer reading time than integrable premises, the corresponding argument will not be included in the fMRI analyses. To anticipate, we found that non-integrable premises for MP arguments fall into this category in the present paradigm. Therefore, our fMRI analyses focus on the two arguments in which processing non-integrable arguments do not require more effort than processing integrable arguments, i.e., MT and RS.

Materials and methods

Participants

Seventeen healthy adults participated in the study. All were right-handed and had normal or corrected-to-normal vision, and no history of neurological or psychiatric disorders. Participants were native French-speakers and gave written informed consent before the experiment. Four participants were excluded due to accuracy rates below 80%. The remaining 13 participants (2 males) were aged between 21 and 29 (mean age: 24 years). Procedures were approved by the local ethics committee (CCPPRB of Lyon, France).

Experimental procedure

Three types of deductive arguments (MP, MT and RS) were used during the experiment (see Fig. 1). Each argument described the conditional (MP, MT) or spatial (RS) relations between several geometrical shapes. A single trial started with the presentation of a first premise (P1), which remained on the screen until participants pressed a key.[5] A visual fixation dot then appeared on the screen for 1 s. This was followed by a second premise (P2), which disappeared when the participants pressed a key. After a variable period of visual fixation (3–5 s), three conclusions (C) appeared on the screen. The participants had to decide which of the three conclusions followed logically from the premises. No time-limit was used (i.e., the conclusions stayed on the screen until the participants provided a response) in order to discourage participants from developing short-cut strategies to solve the problems (Monti et al., 2009; Reverberi et al., 2009). Variable periods of visual fixations were added at the end of each trial (3–5 s).

Conditional and relational arguments were presented in two separate blocks. During the 'conditional' block, participants evaluated 46 conditional arguments. In each of these arguments, the second premise (P2) described a conditional relation between two geometrical shapes (e.g., P2: *If there is a triangle then there is a circle*). In MP-integrable arguments (12 trials), P2 was preceded by a first premise (P1) in which the antecedent of P2 was affirmed (e.g., P1: *There is a triangle*). In MT-integrable arguments (12 trials), P2 was preceded by a first premise in which the consequent of P2 was denied (e.g., P1: *There is not a circle*). Thus, a logically valid conclusion could be inferred by the subjects in MP-integrable (e.g., C: *There is a circle*) and in MT-integrable (e.g., C: *There is not a triangle*) arguments. As baseline for MP-integrable arguments, we included 8 arguments in which P1 was affirmative but not integrable with P2 (e.g., P1: *There is a square*). As baseline for MT-integrable arguments, we included 8 arguments in which P1 was negative but not integrable with P2 (e.g., P1: *There is not a square*). No logical conclusions could be inferred from these non-integrable arguments. To discourage participants from developing expectations, we also included 3 filler trials in which P1 affirmed the consequent of P2 (e.g., P1: *There is a circle*) and 3 filler trials in which P1 denied the antecedent of P2 (e.g., P1: *There is not a triangle*). Finally, we also

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[4] Although Reverberi et al. (2007) found differences showing integrable premises taking longer than non-integrable controls, the difference between the two for Modus Ponens problems was not as strong as for disjunction-elimination problems (see Reverberi et al., 2007, Supplemental materials).

[5] In conditional arguments, the minor premise was presented before the major premise. The reason why this non-traditional order was chosen will be addressed later.
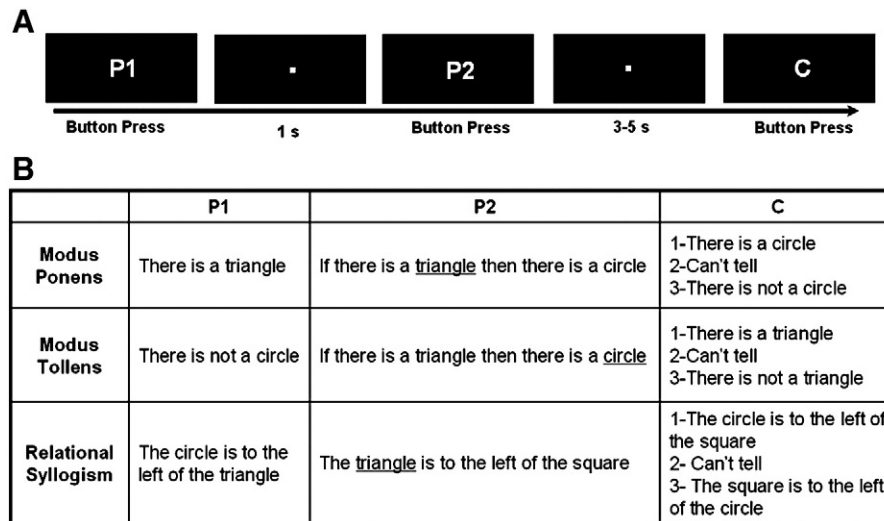
A

B

	P1	P2	C
Modus Ponens	There is a triangle	If there is a <u>triangle</u> then there is a circle	1-There is a circle 2-Can't tell 3-There is not a circle
Modus Tollens	There is not a circle	If there is a triangle then there is a <u>circle</u>	1-There is a triangle 2-Can't tell 3-There is not a triangle
Relational Syllogism	The circle is to the left of the triangle	The <u>triangle</u> is to the left of the square	1-The circle is to the left of the square 2- Can't tell 3- The square is to the left of the circle

Fig. 1. Task and stimuli. (A) Each trial consisted in the sequential presentation of a first premise (P1), a second premise (P2), and a conclusion (C). Premises and conclusion remained on the screen until the participant pressed a key indicating that they were done with the reading of the premises (P1 and P2) or that they selected a conclusion (C). P1 and P2 were separated by 1 s of visual fixation, while P2 and C were separated by 3 to 5 s of fixation. Variable periods of visual fixations were also added at the end of each trial (3–5 s). Only the neural activity related to the presentation of P2 was investigated. (B) Sample arguments used in the experiment. In the non-integrable argument corresponding to each of these integrable deductive arguments, the shape underlined in P2 was replaced by a shape not already mentioned in P1 (e.g., diamond). The underlines did not appear in the task but are there to indicate which words were replaced in the arguments.

included as filler trials 12 arguments in which P2 was a disjunctive statement (e.g., P2: *There is a circle or there is a triangle*). In half of these disjunctive arguments P1 was negative (e.g., P1: *There is not a circle*) while in the other half it was positive (e.g., P1: *There is a circle*).

Unlike most previous behavioral and neuroimaging experiments investigating conditional reasoning (Knauff et al., 2002; Noveck et al., 2004), we presented the minor premise (*There is a triangle*) before the major one (*If there is a triangle then there is a circle*). In a previous behavioral study (Girotto et al., 1997), this type of manipulation has been found to increase the acceptance rate of MT arguments. Here we followed this procedure (also used by Reverberi et al., 2007), to maximize the number of MT arguments accepted in the scanner.

During the 'relational' block, participants evaluated 48 three-term Relational Syllogisms (RS) describing the spatial relationships between three shapes. In 24 of these problems, the second premise (P2) could be integrated with the first one (P1) to produce a logical conclusion (C) (e.g., P1: *The circle is to the left of the triangle*; P2: *The triangle is to the left of the square*; C: *The circle is to the left of the square*). As baseline for these integrable arguments, we included 16 arguments in which P1 and P2 could not be integrated and no conclusion could be inferred by the subjects (e.g., P1: *The circle is to the left of the diamond*; P2: *The triangle is to the left of the square*). Half of these 40 arguments contained the preposition *to the left of* in both P1 and P2, the other half the preposition *to the right of* in both P1 and P2. As filler trials, we also included 6 arguments in which a different preposition was used in P1 and P2 (e.g., P1: *The triangle is to the right of the circle*; P2: *The triangle is to the left of the square*; C: *The circle is to the left of the square*), and 2 arguments in which integrating P1 and P2 lead to an indeterminate conclusion (e.g., P1: *The triangle is to the left of the circle*; P2: *The triangle is to the left of the square*).

Six different shapes were used as materials in the experiment: circle, triangle, square, rectangle, star, and diamond. The order of the trials was randomized within each subject and within each session. Visual stimuli were generated using Presentation software (Neurobehavioral Systems, www.neurobs.com) and projected onto a translucent screen that was viewed by the participants through a mirror attached to the head coil. Participants were trained on the task before entering into the scanner. The practice session consisted of the presentation of two blocks of six trials each (one block of relational and one block of conditional arguments). In each block, participants

evaluated two integrable, two non-integrable and two filler arguments presented in random order. No feedback was provided during or after the training session. All the participants included in the study were above 80% accuracy on conditional and relational arguments after the training session. Overall, the training session lasted about 10–15 min.

Imaging procedures

Images were collected using a 1.5 T MRI scanner (Siemens Sonata Maestro Class; Siemens, Erlangen, Germany) equipped with a standard quadrature head coil. The fMRI blood oxygenation level dependent (BOLD) signal was measured with a T2*-weighted echo-planar sequence (repetition time [TR] = 2500 ms, echo time [TE] = 60 ms). Twenty-six contiguous axial slices (4.40-mm thick, field of view, 23 cm; in-plane resolution, 64×64 matrix) were acquired per volume. Following functional image acquisition, a high-resolution T1-weighted anatomical image (TR = 1880 ms, TE = 3.93 ms, FOV = 256 mm, flip angle = 158, $176 \times 256 \times 256$ matrix, slice thickness = 1 mm) was collected for each subject.

fMRI data analysis

fMRI data were analyzed using SPM5 software (Wellcome Department of Cognitive Neurology, London, UK, http://www.fil.ion.ac.uk). The first 4 volumes in each run were discarded. Functional images were corrected for slice acquisition delays and spatially realigned to the first image of the first run to correct for head movements. The realigned functional images for each subject were then normalized into the Montreal Neurological Institute (MNI) template using an affine transformation and voxels of $3 \times 3 \times 3$ mm^3. Functional images were spatially smoothed with an isotropic Gaussian filter (8-mm full width at half maximum).

Statistical analysis was performed according to the general linear model (Josephs et al., 1997). Filler trials and arguments in which an incorrect response was recorded were excluded from the analyses (i.e., were not included in the statistical model). Trials were sorted by argument (MP, MT, RS) and condition (integrable, non-integrable). All argument sentences (P1, P2 and C) were included in the design matrix, but only sentences corresponding to P2 (the integration phase) were

Table 1
Overall behavioral performance.

Argument	Reaction time (ms)					Accuracy	
	P1	P2 (integrable)	P2 (non-integrable)	C (integrable)	C (non-integrable)	Integrable	Non-integrable
MP	1923 ± 241	2713 ± 179	3542 ± 420	1054 ± 123	1735 ± 235	99 ± 1	85 ± 7[a]
MT	2205 ± 217	3960 ± 244	3689 ± 405	1395 ± 187	1780 ± 200	94 ± 3	92 ± 5[a]
RS	4729 ± 363	5794 ± 502	4465 ± 345	5417 ± 368	2819 ± 176	89 ± 2	98 ± 1

Values are mean reaction times and accuracy $\pm$ SEM. Mean response times are based on correct responses only. SEM = standard error of the mean across participants ($n = 13$). RS: Relational Syllogism, MP: Modus Ponens, MT: Modus Tollens, P1: first premise, P2: second premise, C: conclusion.

[a] Non-integrable here refers to the first premise being affirmative (for what could be potentially a MP argument) or negative (for MT arguments).

considered of interest (with the exception of the conclusion phase of RS which was investigated in a control analysis). For each condition and argument, activation was modeled as epochs with onsets time-locked to the presentation of the corresponding stimulus and with a duration matched to the length of the subject's behavioral response. All epochs were convolved with a canonical hemodynamic response function. The time-series data were high-pass filtered (1/128 Hz) and serial correlations were corrected using an autoregressive AR(1) model.

For each subject and each argument, we calculated the voxelwise contrast representing the integration effect upon the presentation of P2 (i.e., the contrast *integrable vs. non-integrable* arguments). Contrasts were then analyzed in random-effects analyses (using one sample *t*-tests) across subjects. Using a voxelwise height threshold of $p < 0.01$, statistically-defined clusters of activation were identified with whole-brain Monte Carlo simulations (using the AlphaSim program; http://afni.nimh.nih.gov/) to achieve a corrected cluster threshold of $p < 0.05$. However, following Goel et al. (2000) and Noveck et al. (2004), we also report clusters of activation if they survive a voxelwise threshold of $p < 0.001$ (uncorrected) and a symmetrical region is significantly active ($p < 0.05$ corrected clusterwise) in the other hemisphere (i.e., there is anatomical symmetry). This was only the case for the right temporo-parieto-occipital junction (TPO) in the contrast *RS-integrable vs. RS-non-integrable*.

Results

In what follows, we present overall behavioral performance with the aim of confirming past results (e.g. MT arguments should be more difficult to process than MP arguments). We thus describe rates of correct responses to the three types of deductive arguments for which we had integrable and non-integrable premises (MP, MT, and RS). This is followed by an analysis of the reading time of the second premise. Critically, we verify that processing the second premise of non-integrable arguments did not require more effort than processing the second premise of integrable arguments. In the event that non-integrable premises are evidently harder to process than integrable premises, the corresponding argument will be excluded from the fMRI analyses.

Behavioral results

Overall behavioral performance (accuracy and mean reaction times) for each condition is shown in Table 1. Accuracy was high for all integrable arguments (99%, 94% and 89% for MP, MT and RS respectively) and all non-integrable arguments (85%, 92% and 98% for MP, MT and RS forms respectively). Of note, the rate of correct responses for MT arguments (94%) was higher than typically reported in the literature. This is undoubtedly due to the fact that the minor premise was presented before the major premise, as shown by Girotto et al. (1997). To ensure that this high rate of correct responses was not due to some sort of superficial response bias, we compared the reading time of the second premise of MT arguments (i.e., the integration phase investigated in this experiment) to the reading time of the second premise of MP arguments. We found that reading the second premise

of MT arguments took 1.3 s longer than reading the second premise of MP arguments (4 s vs. 2.7 s) and that this difference was highly significant; $t(12) = 7.56, p < 0.001$. Therefore, in our study (as in previous experiments; e.g., Noveck et al., 2004), it can be shown that processing MT arguments is more effortful than processing MP arguments.

Overall, a repeated-measures ANOVA with the factors Problem type (integrable, non-integrable) and Argument (MP, MT, RS) revealed a main effect of Argument ($F(2,24) = 17.67$, $p < 0.001$) and a Problem Type $\times$ Argument interaction ($F(1,24) = 7.05$, $p < 0.01$). Post-hoc analyses (Fischer's LSD) revealed that participants were slower reading the second premise of non-integrable than integrable MP arguments (3.5 s vs. 2.7 s; $p < 0.05$). This effect was observed neither in MT arguments nor in the RS problems. Indeed, the reading time of the second premise of non-integrable MT arguments was comparable to the reading time of integrable MT arguments (4.0 s vs. 3.7 s; $p = 0.15$). Furthermore, reading the second premise of non-integrable RS was faster than reading integrable RS (4.5 s vs. 5.8 s; $p < 0.01$). Given the fact that non-integrable controls for MP arguments were in fact significantly slower to process than integrable MP arguments, we exclude MP from the fMRI analyses. The measure of integration depends on its non-integration control and since it takes an inordinately long time compared to MP, we would not have confidence when interpreting MP integration effects.[6] This is unfortunate, but not entirely unforeseen, as mentioned in the Introduction. Our main concern remains the comparison between propositional and relational inference forms and the two remaining forms, MT and RS, are actually more comparable to each other, with respect to percent correct and reading times.

Because we wanted to discourage participants from using short-cut strategies to perform the task, our experiment was entirely self-paced and no time constraint was used in any phase of the task (including the conclusion evaluation phase). Therefore, although an integration effect was observed during the premise integration phase, it is possible that participants might have just stored the premises in working memory during the integration phase and processed them (at least partially) later on during the conclusion phase. To investigate this hypothesis, we analyzed the difference in reaction time between integrable and non-integrable problems upon the presentation of the conclusion. No difference was found between integrable and non-integrable MT arguments (1.4 s vs. 1.8 s; $t(12) = 1.56$, $p = 0.15$) but a significant difference was observed between integrable and non-integrable RS

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[6] With the aim of replicating the findings from the scanner and to further justify this exclusionary step, we ran 12 participants with the propositional problems containing MP and MT as a behavioral experiment. The results were highly confirming on three counts. First, we found comparable rates of correct evaluations, (97%, 83%, 91%, and 94% for MP-integrable, MP-non-integrable, MT-integrable and MT-non-integrable, respectively). Second, reading the second premise of MT-integrable problems took significantly longer than reading the second premise of MP-integrable problems (2.4 s vs. 1.7 s; $t(11) = 6.16, p < 0.001$). Finally, the reading times for the conditional premise for the four forms (MP-integrable, MP-non-integrable, MT-integrable and MT-non-integrable) were 1.7 s, 2.5 s, 2.4 s, and 2.7 s, respectively. The MP-non-integrable problems alone provided second-premise reading times that took significantly longer to process than its companion integrable versions ($t(11) = 4.00, p < 0.01$).

(5.4 s vs. 2.8 s; $t(12) = 5.86$, $p < 0.001$). This result indicates that MT arguments are fully processed before the appearance of the conclusion, suggesting that all (or most) of the reasoning process takes place during the integration phase. However, the difference in reaction time between integrable and non-integrable RS leaves open the possibility that the RS problems are processed during the conclusion phase as well as during the integration phase. In the following fMRI analyses, we thus investigate, not only the neural activity elicited by the integration of the premises (which is the primary focus of the present manuscript) but, the neural activity elicited by the conclusion of the RS problems as well.

fMRI results

A unitary view of the MLT would posit that reasoning with any kind of deductive argument relies on the brain area typically involved in syntactic processing (i.e., the left IFG) (Goel et al., 2000) or perhaps those that have been recently linked to rule representation (i.e., the left RLPFC and the mSFG) (Monti et al., 2007; Monti et al., 2009). Neuroimaging findings, however, suggest that the engagement of these regions depends upon the type of deductive argument processed (see Introduction). To test this hypothesis, we investigated the brain regions showing a significant integration effect (i.e., greater activation in integrable than non-integrable arguments upon the presentation of P2) in MT arguments and spatial RS. Based on previous literature (Acuna et al., 2002; Goel and Dolan, 2001; Handley et al., 2002; Noveck et al., 2004; Reverberi et al., in press; Reverberi et al., 2007; Vandierendonck and De Vooght, 1997), we predicted that the left IFG would be more engaged in MT arguments than in the RS problems. We furthermore anticipated that the RS problems would preferentially activate the visuo-spatial regions of the parieto-occipital cortex.

Modus Tollens arguments

We predicted that MT arguments would especially rely on the region associated with syntactic processing in language, i.e., the left IFG. Our analyses revealed an integration effect associated with MT arguments in the left IFG ($x = -24$ $y = -97$ $z = 2$, $t = 5.44$), left insula ($x = -33$ $y = 14$ $z = 14$, $t = 5.49$), bilateral middle occipital gyrus (left MOG; $x = -33$ $y = -91$ $z = 14$, $t = 3.05$; right MOG; $x = 27$ $y = -88$ $z = 11$, $t = 5.92$) and left lingual gyrus (LG; $x = -3$ $y = -91$ $z = 2$, $t = 8.03$) (Table 2 and Fig. 2). Consistent with our hypothesis, these findings show that integrating MT arguments engages the brain region central to syntactic processing (i.e., the left IFG; Friederici and Kotz, 2003). They also show enhanced activity in regions of the primary visual cortex, a result that
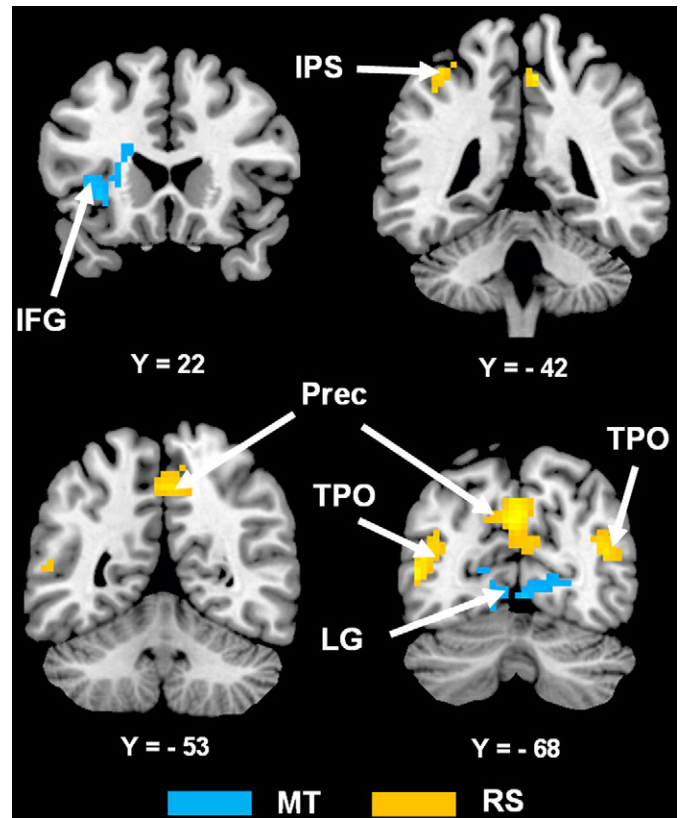

Fig. 2. Brain regions showing an integration effect (i.e., more activity in integrable than non-integrable arguments upon the presentation of the second premise) in Modus Tollens arguments (MT) and Relational Syllogisms (RS). An integration effect associated with MT arguments (blue) was observed in the left inferior frontal gyrus (IFG) and bilateral lingual gyrus (LG), whereas an integration effect associated with the RS problems (yellow) was observed in the bilateral temporo-parieto-occipital junction (TPO), left intraparietal sulcus (IPS) and precuneus (Prec). Activations are overlaid on slices of the MNI-normalized anatomical brain.

Table 2
Brain regions showing an integration effect (i.e., more activity for integrable arguments than for non-integrable arguments) in Modus Tollens arguments and Relational Syllogisms.

Anatomical location	~BA	Talairach coordinates			t-score
		x	y	z	
Modus Tollens (MT)					
L. lingual gyrus	17	−3	−91	2	8.03
R. middle occipital gyrus	19	27	−88	11	5.92
L. insula	13	−33	14	14	5.49
L. inferior frontal gyrus	47	−33	20	−4	4.28
L. middle occipital gyrus	19	−33	−91	14	3.05
Relational Syllogism (RS)					
L. precuneus	7	−3	−73	38	5.32
L. temporo-parieto-occipital junction	39/19	−48	−73	14	5.10
L. temporo-parieto-occipital junction	37	−48	−70	−2	3.18
R. precentral gyrus	4/6	51	−13	38	4.02
R. temporo-parieto-occipital junction	39/19	42	−70	23	4.42
L. precentral gyrus	4/6	−51	−13	38	4.82
L. inferior parietal lobule	40	−57	−37	44	4.82

Notes. L., left; R. right; ~BA, approximate Brodmann's area.

might be explained by differences in attentional processing between integrable and non-integrable problems (see Discussion).

Relational Syllogisms

We predicted that the RS problems would not activate the left IFG, but would rather rely on parieto-occipital regions. We found a significant integration effect associated with the RS problems in a network encompassing the bilateral temporo-parieto-occipital junction (TPO; left: $x = -48$ $y = -73$ $z = 14$, $t = 5.10$; right: $x = 42$ $y = -70$ $z = 23$, $t = 4.42$), the left intraparietal sulcus (IPS; $x = -57$ $y = -37$ $z = 44$, $Z = 4.82$), the left precuneus ($x = -3$ $y = -73$ $z = 38$, $t = 5.32$), (Table 2 and Fig. 2) and the bilateral precentral gyrus (left: $x = -51$ $y = -13$ $z = 38$, $t = 4.82$; right: $x = 51$ $y = -13$ $z = 38$, $t = 4.82$). No activation was observed in either the left IFG or even in the regions recently assumed to be involved in rule-based processing in reasoning (left RLPFC and mSFG; Monti et al., 2007; Monti et al., 2009). These results suggest that integrating the premises of relational arguments does not depend on the brain regions typically associated with syntactic or rule-based processing, but instead engages a network of parietal, occipital and temporal brain regions.

Even though the results above support our predictions about neural activity during the premise integration phase, it is possible that the regions involved in syntactic and rule-based processes are activated later on, i.e., during the conclusion phase. The fact that some reasoning may occur not only during the premise integration phase but also during the conclusion phase is suggested by our behavioral data. In the RS problems, unlike in the MT arguments, we
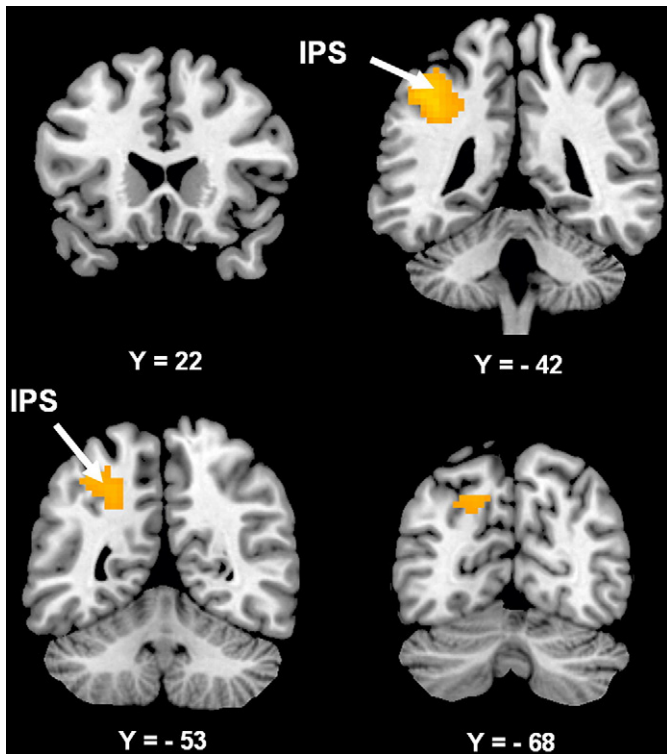
Fig. 3. Conclusion phase of Relational Syllogisms (RS). Greater activity for integrable than non-integrable RS upon the presentation of the conclusion was observed in the left intraparietal sulcus (IPS) but not in the left inferior frontal gyrus. Activations are overlaid on slices of the MNI-normalized anatomical brain.

found that participants took more time to choose the conclusion of integrable problems than to decide that the conclusion of non-integrable problems was undetermined. To assess whether any brain regions involved in syntactic and rule-based processing were activated during the conclusion phase of the RS problems, we thus contrasted integrable vs. non-integrable problems upon the presentation of the conclusion (Fig. 3). We found greater activation for integrable than non-integrable RS in the left IPS ($x = -39$ $y = -49$ $z = 53$, $t = 6.10$) and left precentral gyrus ($x = -48$ $y = 5$ $z = 35$, $t = 7.91$), but no activation in the left IFG, left RLPFC or mSFG. This result confirms that none of the areas assumed to be associated with the MLT are activated in RS, whether one considers the integration or conclusion phase.

Overall, the findings reported above indicate that the integration effect in MT arguments is associated with activation of the left IFG, while the integration effect in RS is associated with activation of several temporo-parieto-occipital regions. To determine whether reasoning-related activity in some of these regions is biased towards a specific argument, we directly compared the size of the integration effect between MT arguments and RS across the whole-brain. Specifically, we predicted a greater integration effect for MT arguments than RS in the left IFG, and a greater integration effect for RS than MT arguments in parieto-occipital regions.

Modus Tollens arguments vs. Relational Syllogisms

We first identified the regions showing a greater integration effect associated with MT arguments than RS. As predicted, a larger integration effect in MT arguments than in RS was found in the left IFG ($x = -39$ $y = 22$ $z = 2$, $t = 4.64$) and the left insula ($x = -33$ $y = 17$ $z = 2$, $t = 5.33$) (Table 3 and Fig. 4A).

Relational Syllogisms vs. Modus Tollens arguments

We then compared the integration effect associated with RS to the one related to MT arguments. The integration effect was greater in RS

Table 3
Brain regions in which the size of the integration effect is modulated by the type of deductive argument (Modus Tollens vs. Relational Syllogism).

Anatomical location	~BA	Talairach coordinates			t-score
		x	y	z	
Modus Tollens > Relational Syllogism					
L. insula	13	−33	17	2	5.33
L. inferior frontal gyrus	47	−39	22	2	4.64
Relational Syllogism > Modus Tollens					
R. temporo-parieto-occipital junction	22/39	54	−58	14	6.10

Notes. L., left; R. right; ~ BA, approximate Brodmann's area.

than in MT arguments only in the right TPO ($x = 54$ $y = -58$ $z = 14$, $t = 6.10$) (Table 3 and Fig. 4B).

Discussion

The goal of the present fMRI experiment was to examine whether the materials in the logical argument determines the engagement of the neural system, with syntactic or rule-based processing linked to conditional propositions and visuo-spatial processing linked to relational reasoning. Participants were presented with conditional and relational arguments, along with their respective baselines (cases where a premise could not be integrated). Specifically, we compared the neural activity elicited by the presentation of the second premise (i.e., the integration phase, Reverberi et al., 2007; Rodriguez-Moreno and Hirsch, 2009) of MT and RS arguments. Consistent with previous findings (Noveck et al., 2004; Reverberi et al., in press; Reverberi et al., 2007), we found that conditional arguments (i.e., MT) are associated with enhanced activation in the left IFG. However, this effect was specific to conditional arguments. Indeed, the left IFG was engaged neither during the integration phase nor the conclusion phase of the RS problems. Instead, integrating the premises (as well as evaluating the conclusion) of the RS problems was associated with enhanced activity in several regions of a temporo-parieto-occipital network.

Previous behavioral findings suggest that conditional arguments rely more on syntactic processes than RS (Handley et al., 2002). Here we found that integrating the premises of MT arguments was associated with enhanced activity in the left IFF (BA 47), whereas integrating the premises of the RS problems was not related to increased activity in this area. Critically, the only brain region showing a greater integration effect in MT arguments over the RS arguments was the left IFG. Our findings are in line with previous neuroimaging results investigating the neural
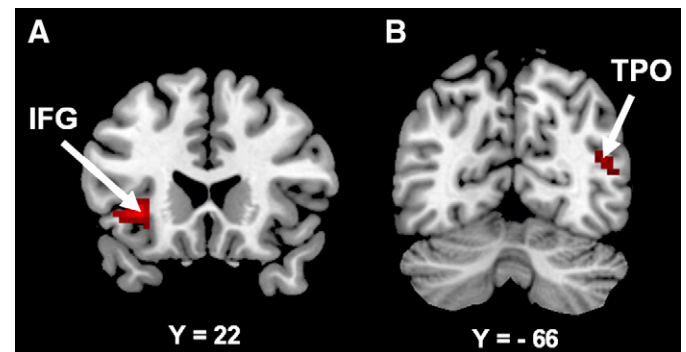

Fig. 4. Brain regions in which the size of the integration effect (i.e., difference in activity between integrable than non-integrable arguments upon the presentation of the second premise) is modulated by the type of deductive argument. (A) Modus Tollens (MT) arguments were associated with a greater integration effect than Relational Syllogisms (RS) in the left IFG. (B) RS were associated with a greater integration effect than MT arguments in the right temporo-parieto-occipital junction. Activations are overlaid on slices of the MNI-normalized anatomical brain.

activity associated with endorsing the conclusion of conditional arguments such as MT. Both Noveck et al. (2004) and Monti et al. (2007) observed that evaluating the conclusion of MT arguments is linked to enhanced activity in the left IFG. Similarly, Reverberi et al. (2007) and Reverberi et al. (in press) found that integrating the premises of conditional arguments is associated with left IFG activation. A large body of evidence coming from lesions and neuroimaging studies has implicated the left IFG (both BA 44/45 and BA47) in syntactic processing at the word or sentence level (Friederici and Kotz, 2003; Grodzinsky and Santi, 2008). Therefore, the greater activation of the left IFG in MT arguments than in RS is in line with the proposal that conditional arguments rely more on syntactic mechanisms than RS (Handley et al., 2002).

Prior neuroimaging research supports the idea that relational arguments engage the visuo-spatial mechanisms of the parieto-occipital cortex rather than the syntactic or rule-based mechanisms of the frontal cortex (Acuna et al., 2002; Fangmeier and Knauff, 2009; Fangmeier et al., 2006; Goel et al., 2004; Heckers et al., 2004; Knauff et al., 2003). In line with these studies, we found that integrating the premises of the RS problems was associated with increased activity in several parietal and occipital regions. We also found increased activity in the bilateral precentral gyrus, a region in which activity during relational reasoning has been interpreted as reflecting mental rotation and attentional modulation of motor responses (Acuna et al., 2002). Critically, no activation was observed in any of the brain regions that have been associated with syntactic or rule-based processing (left IFG, left RLPFC, mSFG), and only the right TPO showed a larger integration effect in RS than MT arguments. This finding suggests that the right TPO (BA 39/19) plays a more important role in relational reasoning than in conditional reasoning. Previous lesion and neuroimaging studies support the idea that regions around the TPO are important for relational reasoning. For example, it has been shown that bilateral lesions at the level of the TPO are associated with impaired understanding of spatial logical relationships (Hier et al., 1980). In healthy subjects, neuroimaging studies have demonstrated that endorsing the conclusion of three-term linear syllogisms (similar to those used in the present study) is linked to enhanced activation in and around the bilateral TPO (Goel and Dolan, 2001; Knauff et al., 2002), and that this conclusion-related activation is greater for relational than for conditional problems (Knauff et al., 2002). More generally, fMRI activations in and around the TPO (particularly in the occipital cortex) have been associated with the generation and the manipulation of spatial mental images (D'Esposito et al., 1997; Mellet et al., 2002). Therefore, the greater involvement of the TPO in RS than MT arguments is consistent with the claim that relational arguments rely more on visuo-spatial mechanisms than conditional arguments, as suggested by previous behavioral studies (Vandierendonck and De Vooght, 1997).

Overall, our findings demonstrate that MT arguments and RS involve largely separate neural systems. A recent study by Reverberi et al. (in press) also revealed a dissociation between the brain regions associated with the integration phase of conditional problems (e.g., *if a thing is x then it is y; if a thing is y then it is z // If a thing is x then it is z*) and categorical syllogisms (e.g., *everything x is y; nothing y is z // nothing x is z*). Specifically, the authors showed a greater integration effect associated with categorical syllogisms than conditional problems in the left parietal and left ventral IFG, while a more dorsal part of the left IFG was activated for both types of problems. On the one hand, the latter result suggests that syntactic mechanisms may play a role in both conditional arguments and categorical syllogisms. On the other hand, the former finding demonstrates some degree of dissociation between conditional arguments and categorical syllogisms. Taken together, this study and the present experiment suggest that the neural system underlying deductive reasoning depends (at least partially) upon the type of deductive argument processes (that is, conditional vs. relational vs. categorical syllogism). In fact, the more general idea that deductive reasoning engages a fractionated brain system has been recently put forward by Goel (2007), who proposed that the neuroanatomy of deduction depends upon factors such as familiarity with the semantic content of the premises, prior beliefs and uncertainty of the problems. The present study suggests that the type of deductive argument may also be an important factor that affects the neural bases of reasoning.

The present data fit well with the existing behavioral and neuroimaging literature on deductive reasoning. However, it is important to consider the possibility that the effects observed here reflect processes other than reasoning. Specifically, it has been argued that the results obtained in prior neuroimaging studies might be partially due to differences in attentional engagement between deductive and baseline arguments (Bonnefond and Van der Henst, 2009; Monti et al., 2007). Here we verified that non-integrable premises (i.e., the baseline arguments) were not harder to process than integrable premises before turning to the fMRI analyses. Because this criterion was met only for MT arguments and RS (but not for MP arguments), we only analyzed the neural integration effect associated with MT arguments and RS. However, it is also possible that this neural integration effect reflects, at least partially, differences in attentional and reading processes between integrable and non-integrable arguments instead of differences in reasoning processes. Indeed, reasoners might give the correct answer in non-integrable arguments without having to read the second premise in its entirety. Consider for example a relational argument starting with the first premise *The circle is to the left of the triangle*. In non-integrable arguments, this first premise can be followed by, e.g., the premise *The diamond is to the left of the square*. As one can see, reasoners might adopt a strategy whereby the first word of the second premise is indicative of rejecting the argument as non-integrable. In contrast, one always needs to read the second premise of valid arguments in its entirety (e.g., *The triangle is to the left of square*) to infer a correct conclusion. Therefore, any differences observed between these argument types could be attributable to differences in attention or reading processes. Although we tried to limit this strategy by including filler arguments in our experiment,[7] it is possible that the occipital activations observed in the integrable vs. non-integrable contrast for MT arguments are due to reading or attentional processes not specific to reasoning. It is thus important to note that the most critical results of the present study are based on direct comparisons between the size of the integration effect associated with MT arguments and RS. In other words, these contrasts allowed us to compare the neural activity associated with different integrable (and thus fully processed) arguments, while controlling for the superficial structure of the second premise (by subtracting out the activity associated with the second premise of non-integrable arguments). Therefore, the results obtained in the left IFG and right TPO seem to be best explained by differences in reasoning processes than by other factors like variations in attentional engagement or differences in the stimulus structure.

In sum, we demonstrate that the left IFG is activated more during MT arguments than spatial RS, while the right TPO is activated more during spatial RS than MT arguments. More generally, the present experiment shows that reasoning with conditional and relational statements does not engage the same neural structures. Our conclusions are in line with recent claims about dissociations within the neural correlates of deductive reasoning (Goel, 2007; Reverberi et al., in press). However, they also deviate from the conclusion of two recent studies arguing that deduction relies on two "core" brain regions, namely the left RLPFC and the mSFG (Monti et al., 2007; Monti et al., 2009). In the present study, as in many others (Acuna et al., 2002; Fangmeier et al., 2006; Goel et al., 2000; Goel and Dolan, 2001; Knauff et al., 2003; Noveck et al., 2004; Parsons and Osherson, 2001; Reverberi et al., in press; Reverberi et al., 2007), we failed to find any reasoning-related activation in these regions. The discrepancy

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[7] Consider how participants were required to read the second premise throughout in filler arguments with premises such as *The circle is to the left of the triangle* and *The diamond is to the right of triangle*.

between our results and those of Monti et al. (2007) and Monti et al. (2009) might be partially explained by differences in complexity between the stimuli used. Indeed, the authors of these two studies used much more complex deductive tasks than ours (e.g., disjunctions embedded in MT problems; Monti et al., 2007; and complexly worded conditional statements; Monti et al., 2009). We speculate that increased activity in the left RLPFC and mSFG is triggered by the complexity of the task and might not be observed in simpler tasks such as those used in the present study. Instead of relying on two "core" regions, we propose that deduction is supported by a functionally heterogeneous brain system.

Here we demonstrate that two different arguments engage different brain regions, and suggest that these dissociations are due to the type of deductive argument (conditional vs. relational). However, it is also possible that the patterns of activity that we observe are specific to MT arguments and the spatial RS, and might be different if one focuses on, e.g., simpler MP arguments and RS with non-spatial relations. Future studies comparing different deductive arguments are needed to isolate the critical factors driving the neural dissociations observed in reasoning. This is critical in order to determine to what extent the neural system underlying deductive reasoning is fractionated.

Acknowledgments

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