Brief article

Explaining modulation of reasoning by belief

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Abstract

Although deductive reasoning is a closed system, one's beliefs about the world can influence validity judgements. To understand the associated functional neuroanatomy of this belief-bias we studied 14 volunteers using event-related fMRI, as they performed reasoning tasks under neutral, facilitatory and inhibitory belief conditions. We found evidence for the engagement of a left temporal lobe system during belief-based reasoning and a bilateral parietal lobe system during belief-neutral reasoning. Activation of right lateral prefrontal cortex was evident when subjects inhibited a prepotent response associated with belief-bias and correctly completed a logical task, a finding consistent with its putative role in cognitive monitoring. By contrast, when logical reasoning was overcome by belief-bias, there was engagement of ventral medial prefrontal cortex, a region implicated in affective processing. This latter involvement suggests that belief-bias effects in reasoning may be mediated through an influence of emotional processes on reasoning. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

Deductive reasoning is the process of drawing valid conclusions from a given set of premises. From a strictly logical point of view it is a closed system, although it is well known that beliefs about the conclusion of an argument influence people's validity judgements. Consequently, subjects perform better on syllogistic reasoning tasks when the truth value of a conclusion (true or false) coincides with the logical relationship between

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premises and conclusion (valid or invalid). In other words, if the logical conclusion is consistent with beliefs about the world, the beliefs are facilitatory to the logical task. For example, the following valid argument with a believable conclusion is accepted as valid 96% of the time:

No cigarettes are inexpensive.
Some addictive things are inexpensive.
∴ Some addictive things are not cigarettes.

By contrast, a logically identical argument with an unbelievable conclusion is accepted as valid only 46% of the time (Evans, Barston, & Pollard, 1983):

No addictive things are inexpensive.
Some cigarettes are inexpensive.
∴ Some cigarettes are not addictive.

Hence, if the logical conclusion is inconsistent with beliefs about the world, the beliefs are inhibitory to the logical task. Performance on arguments that are belief-neutral usually falls between these two extremes (Evans, Handley, & Harper, 2001).

One explanation for belief-bias effects is offered by a dual mechanism theory of reasoning. Dual mechanism theories come in various flavours that differentially emphasize explicit and implicit processes (Evans et al., 1983), conscious and preconscious processes (Stanovich & West, 2000), formal and heuristic processes (Newell & Simon, 1972), and associative and rule-based processes (Goel, 1995; Sloman, 1996). The relationship among these proposals has yet to be clarified. But at a very crude level, such theories make a distinction between formal, deliberate, rule-based processes and implicit, unschooled, automatic processes and would arguably predict the involvement of two different brain systems in human reasoning.

A recent fMRI study (Goel, Buchel, Frith, & Dolan, 2000) has provided evidence that syllogistic reasoning is implemented in two distinct brain systems whose engagement is primarily a function of the presence or absence of meaningful content. During content-based syllogistic reasoning (e.g. All apples are red fruit; All red fruit are poisonous; ∴ All apples are poisonous) a left hemisphere frontal and temporal lobe system is recruited. By contrast, in a formally identical reasoning task with arbitrary content (e.g. All A are B; All B are C; ∴ All A are C) a bilateral parietal system is recruited. Given these dissociable systems, one can explain performance differences between arguments with meaningful and arbitrary content by appealing to differential efficiency and/or engagement of the two systems. But the use of variables in the arbitrary condition leaves open the possibility that the modulation between the two systems is a function of concrete vs. abstract content rather than belief-laden vs. belief-neutral content. It also does not explain how inhibitory and facilitatory beliefs (within the belief-laden reasoning system) modulate the reasoning process. In the present study we demonstrate that belief-laden and belief-neutral arguments are sufficient to modulate between temporal and parietal systems. Furthermore, we demonstrate distinct roles for lateral prefrontal and ventro-medial prefrontal cortex in modulation of reasoning by beliefs.

2. Method

2.1. Subjects

We scanned 14 right-handed normal subjects using event-related fMRI, to index task-related neural activity, while they engaged in deductive reasoning. Seven right-handed males and seven right-handed females with a mean age of 30.8 years (SD = 4.3) and a mean education level of 16.8 years (SD = 2.0) volunteered to participate in the study. All subjects gave informed consent and the study was approved by the Joint National Hospital for Neurology and Neurosurgery/Institute of Neurology Ethics Committee.

2.2. Stimuli

One hundred twenty syllogisms, encompassing 15 different forms,[1] and 40 baseline items were organized into a nested 2 × 2 factorial design (Fig. 1a). At the top level the first factor was *Belief*, consisting of two levels, belief-laden (80 syllogisms and 40 baseline) and belief-neutral (40 syllogisms and 20 baseline) items. (The increased number of belief-laden trials is due to their further subdivision below.) The belief-laden trials (e.g. No reptiles are hairy; Some elephants are hairy; ∴ No elephants are reptiles) contained content sentences that subjects could be expected to have beliefs about, while the belief-neutral trials (e.g. No codes are highly complex; Some quipu are highly complex; ∴ No quipu are codes) contained sentences that subjects may not have beliefs about (because they may not know the meaning of one or more key terms). The non-logical key terms in both conditions were matched for category (living things, objects, abstract ideas). The logically relevant information in both conditions was identical. The final allocation of trials to conditions was determined for each subject by a post-scan questionnaire that asked subjects to demonstrate their beliefs by rating the conclusion of each argument as either 'true', 'false', or 'unsure'.

The second factor was *Task* in which the first level (a reasoning condition) involved stimuli that constituted arguments (120 trials as in the examples above and below). Half of these were valid while the other half were not valid. The second level (baseline condition) trials were generated by taking these arguments and switching around the third sentence such that the three sentences did not constitute arguments. This resulted in 40 belief-laden baseline trials (e.g. No reptiles are hairy; Some elephants are hairy; ∴ No pairs are green) and 20 belief-neutral baseline trials (e.g. No codes are highly complex; Some quipu are highly complex; ∴ No monorchids are gibbed).

To directly examine belief–logic interactions, the arguments that subjects could have beliefs about (first cell of the main factorial) was further subdivided into 40 facilitatory and 40 inhibitory belief trials. The facilitatory trials consisted of valid trials with believable conclusions (e.g. Some children are not Canadians; All children are people; ∴ Some people are not Canadians) and invalid trials with unbelievable conclusions (e.g. Some violinists are not mutes; No opera singers are violinists; ∴ Some opera singers are mutes)

a

Reasoning Condition		Belief-Laden		Belief-Neutral
		Valid	Invalid	
	True	No poisons are sold at the grocers. Some mushrooms are sold at the grocers. Some mushrooms are not poisonous.	No reptiles can grow hair. Some elephants can grow hair. No elephants are reptiles.	Some monorchids are ground rhumbs. All ground rhumbs are rare. Some monorchids are not rare.
	False	Some green amphibians are toads. All green amphibians are frogs. Some frogs are toads.	No unhealthy foods have cholesterol. Some unhealthy foods are fried foods. No fried foods have cholesterol.	
Baseline		No poisons are sold at the grocers. Some mushrooms are sold at the grocers. Some frogs are toads.		Some monorchids are ground rhumbs. All ground rhumbs are rare. Some gimbel functions are not provable.

b

Event-Related
Stimuli Presentation

Task: Is argument valid?

3 12.3 min repetitions
60 event presentations
TR=4.1 sec
Random Jitter

*   S1   S1   S1
                     S2   S2
                                 S3

Motor
Response
(Time Variable)

Reasoning

0 0.5   3.5   6.5   10.25-14.35sec

Stimuli Presentation
Reading/Integrating
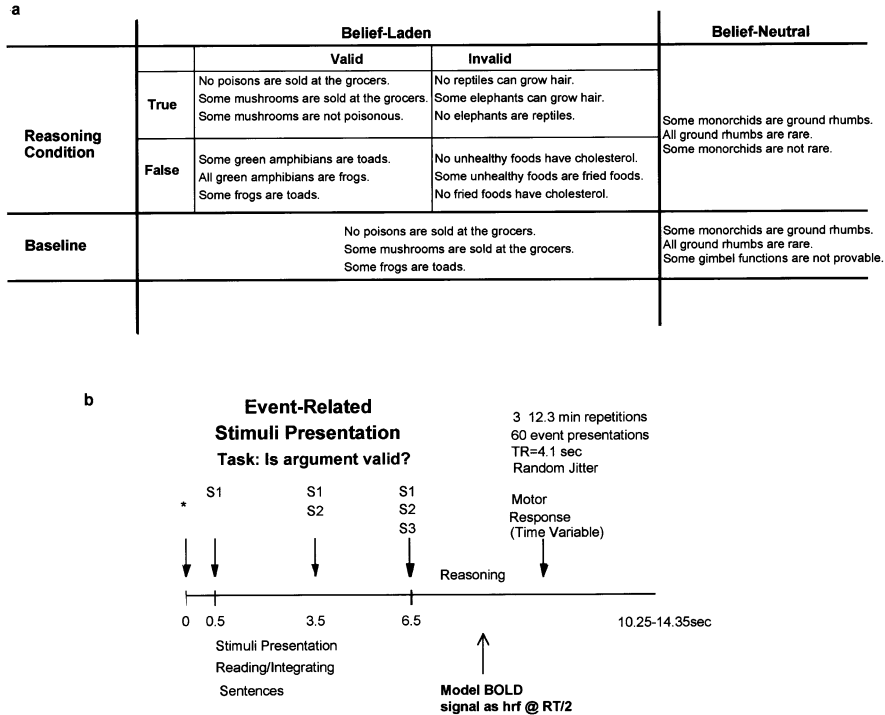Sentences

Model BOLD
signal as hrf @ RT/2

Fig. 1. (a) Overall design of the study with sample stimuli. (b) The arguments were visually presented one sentence at a time. Subjects responded after the presentation of the third sentence (conclusion). Reasoning processes were modelled as a HRF at the half way point between the presentation of the conclusion and the motor response, on a trial by trial, subject by subject basis. See text.

such that subjects' beliefs were facilitatory to the logical task. The inhibitory belief trials consisted of valid trials with unbelievable conclusions (e.g. No harmful substances are natural; All poisons are natural; ∴ No poisons are harmful) and invalid trials with believable conclusions (e.g. All calculators are machines; All computers are calculators; ∴ Some machines are not computers) such that subjects' beliefs were inhibitory to the logical task.[2] All sentences were grammatical, meaningful, and matched for length across conditions.

Stimuli from all conditions were presented randomly in an event-related design (see Fig. 1). An "*" indicated the start of a trial at 0 s. The sentences appeared on the screen one at a time with the first sentence appearing at 500 ms, the second at 3500 ms, and the last sentence at 6500 ms. All sentences remained on the screen until the end of the trial. The length of trials varied from 10.25 to 14.35 s, leaving subjects 3.75–7.85 s to respond. The task in *all* conditions was the same. Subjects were required to determine whether the conclusion followed logically from the premises (i.e. whether the argument was valid). Subjects responded by pressing a button on a keypad after the appearance of the last sentence.

In (reasoning condition) trials where the three sentences constituted an argument, subjects had to determine the validity of the argument. In (baseline) trials, where the third sentence was unrelated, subjects would begin to construct a representation of the problem, but could disengage and respond 'no' with the appearance of the third unrelated sentence. Subjects were instructed to respond as quickly as possible and move to the next trial if the stimuli advanced before they could respond. Subjects reviewed example stimuli from each condition prior to being scanned to ensure that they understood the task. Subjects were not given feedback about their performance during the experiment.

2.3. fMRI scanning technique

A 2T Siemens VISION system (Siemens, Erlangen, Germany) was used to acquire T1 anatomical volume images ($1 \times 1 \times 1.5$ mm voxels) and 48 T2*-weighted echoplanar images (64×64 3×3 mm pixels, TE = 40 ms) sensitive to blood oxygenation level dependent (BOLD) contrast. Echoplanar images (1.8 mm thick) were acquired axially every 3 mm, positioned to cover the whole brain. Data were recorded during a single acquisition period. A total of 558 volume images were acquired over three sessions (186 volumes per session) with a repetition time (TR) of 4.1 s/volume. The first six volumes in each session were discarded (leaving 180 volumes per session) to allow for T1 equilibration effects.

Trials from all conditions were randomly presented in a single-event design. The mean trial time was 12300 ± 2050 ms (TR) with a random jitter. Trials thus varied from 10.25 to 14.35 s. There were 60 event presentations during a session for a total of 180 over the three sessions. Each session lasted 12.3 min. The scanner was synchronized with the presentation of all trials in each session.

2.4. Data analysis

Data were analyzed using Statistical Parametric Mapping (SPM 99) (Friston et al., 1995). All volumes were spatially realigned to the first volume (head movement was <2 mm in all cases) and temporally realigned to the AC-PC slice, to account for different sampling times of different slices. A mean image created from the realigned volumes was coregistered with the structural T1 volume and the structural volumes spatially normalized to the Montreal Neurological Institute brain template (Evans, Collins et al., 1993) using non-linear basis functions (Ashburner & Friston, 1999). The derived spatial transformation was then applied to the realigned T2* volumes, which were finally spatially smoothed with a 12 mm FWHM isotropic Gaussian kernel (in order to make comparisons across subjects and to permit application of random field theory for corrected statistical inference; Worsley & Friston, 1995). The resulting time series across each voxel were high-pass filtered with a cut-off of 32 s, using cosine functions to remove section-specific low frequency drifts in the BOLD signal. Global means were normalized by proportional scaling to a Grand Mean of 100, and the time series temporally smoothed with a canonical hemodynamic response function to swamp small temporal autocorrelations with a known filter.

Condition effects at each voxel were estimated according to the general linear model and regionally specific effects compared using linear contrasts. Each contrast produced a

Table 1
Behavioural performance scores and reaction times on task

	Performance scores (SD)		Reaction times (SD)	
	Belief (%)	Non-belief (%)	Belief (ms)	Non-belief (ms)
All reasoning trials	73.9 (12.5)	66.6 (15.2)	3360 (560)	3436 (429)
Facilitatory trials	83.4 (8.7)	N/A	3293 (551)	N/A
Inhibitory trials	64.5 (18.9)	N/A	3438 (615)	N/A
Baseline trials	97.5 (1.4)	98.6 (2.3)	1642 (384)	1640 (347)

statistical parametric map of the *t*-statistic for each voxel, which was subsequently trans-formed to a unit normal *Z*-distribution. The activations reported survived a voxel-level intensity threshold of $P < 0.05$ (corrected for multiple comparisons) using a random effect model. An exception was made in the case of interactions. An uncorrected threshold of $P < 0.001$ was used for interactions as they were inclusively masked by the main effect (approximating the joint probability of both effects). Where an anatomical structure was significantly active in one hemisphere, we report any activation in the corresponding structure in the other hemisphere, even if it does not survive correction for multiple comparisons. The BOLD signal was modelled as a HRF at the midway point between the presentation of the third sentence and the motor response on a subject by subject and trial by trial basis. The presentation of all three sentences along with the motor response were modelled out in the analysis. All activations surviving correction for multiple comparisons are reported.

3. Results

Behavioural scores indicated that subjects performed the task in the expected manner (Table 1). Percent correct scores were significantly higher (98.0% (SD = 1.5)) in the baseline condition than the reasoning condition, with no difference between belief-laden and belief-neutral baseline conditions. Subjects' performance on the reasoning task exhib-ited a belief-bias effect. Percent correct scores were significantly higher ($t(13) = 2.99$, $P < 0.05$) for belief-laden arguments (73.9% (SD = 12.5)) than belief-neutral arguments (66.6% (SD = 15.2)). Subjects had significantly higher correct scores in facilitatory belief trials (i.e. valid argument and true conclusion and invalid argument and false conclusion) (83.4% (SD = 8.7)) than in inhibitory belief trials (i.e. valid argument and false conclu-sion and invalid argument and true conclusion) (64.5% (SD = 18.9)) ($t(13) = 4.6$, $P < 0.05$). Subjects took a mean of 3360 ms (SD = 560) (after presentation of the third sentence at 6500 ms) to respond to belief-laden and 3436 ms (SD = 429) to belief-neutral arguments. This difference did not reach statistical significance. The mean reaction time for facilitatory trials was 3293 ms (SD = 551) compared to 3438 ms (SD = 615) for inhibitory trials. The difference did not reach statistical significance. The mean reaction times for the baseline condition were the fastest and significantly lower (1640 ms (SD = 360)) than the reasoning condition.

The simple effect of belief on reasoning was determined by comparisons of belief-laden and belief-neutral reasoning trials (correct trials only). The direct comparison of belief-neutral reasoning with belief-laden reasoning (correct belief-neutral trials − correct belief-laden trials) (masked by the main effect of reasoning) resulted in activation of (a) bilateral (L > R) superior parietal lobule (−21, −63, 54; $Z = 4.69$ and 21, −60, 54; $Z = 4.03$) (BA 7) (Fig. 2a). The reverse comparison of belief-laden reasoning with belief-neutral reasoning (correct belief-laden trials − correct belief-neutral trials) (masked by main effect of reasoning) resulted in activation of the left pole of middle temporal gyrus (−48, 12, −39; $Z = 5.28$) (BA 21) (Fig. 2b). The Task (reasoning and baseline) by Belief (belief-laden and belief-neutral) interaction (masked by the main effect of reasoning relative to baseline) revealed similar results. Modulation of the reasoning task by absence of belief [(belief-neutral reasoning − belief-neutral baseline) − (belief-laden reasoning − belief-laden baseline)] revealed activation in the left superior parietal lobe (BA 7) (−6, −54, 45; $Z = 4.27$) unique to the belief-neutral condition. The reverse modulation [(belief-laden reasoning − belief-laden baseline) − (belief-neutral reasoning − belief-neutral baseline)] revealed activation of the anterior left middle temporal gyrus (BA 21) (−51, 15, −27; $Z = 3.58$) unique to the belief-bias condition.

To examine the mechanisms underlying belief–logic interactions we restricted our subsequent analysis to belief-laden reasoning trials. Neither the comparison of (correct and incorrect) inhibitory trials with (correct and incorrect) facilitatory trials, nor the reverse comparison of (correct and incorrect) facilitatory trials with (correct and incorrect) inhibitory trials revealed any significant activation.[3] But within the inhibitory belief trials, a comparison of correct items with incorrect items (correct inhibitory belief trials − incorrect inhibitory belief trials) revealed activation of right inferior prefrontal cortex (51, 21, 12; $Z = 4.58$) (BA 45) (Fig. 2c). The reverse comparison of incorrect response trials with the correct response trials (incorrect inhibitory belief trials − correct inhibitory belief trials) revealed activation of ventral medial prefrontal cortex (VMPFC) (3, 33, −15; $Z = 4.62$) (Fig. 2d). An examination of condition specific parameter estimates (Fig. 2e) shows that the response of the VMPFC is specific to inhibitory belief trials and its activation during incorrect trials is enhanced by its relative deactivation (with respect to facilitatory belief trials) during correct inhibitory belief trials.[4]

4. Discussion

The results regarding the effect of belief on reasoning replicate our previous study (Goel et al., 2000) and provide additional evidence for a dual mechanism theory of reasoning, involving a left temporal lobe system and a bilateral parietal system. Consistent with our claim that belief-laden reasoning involves a left temporal system are findings that implicate this system in the semantic retrieval and selection of information (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill et al., 1998). By contrast, the
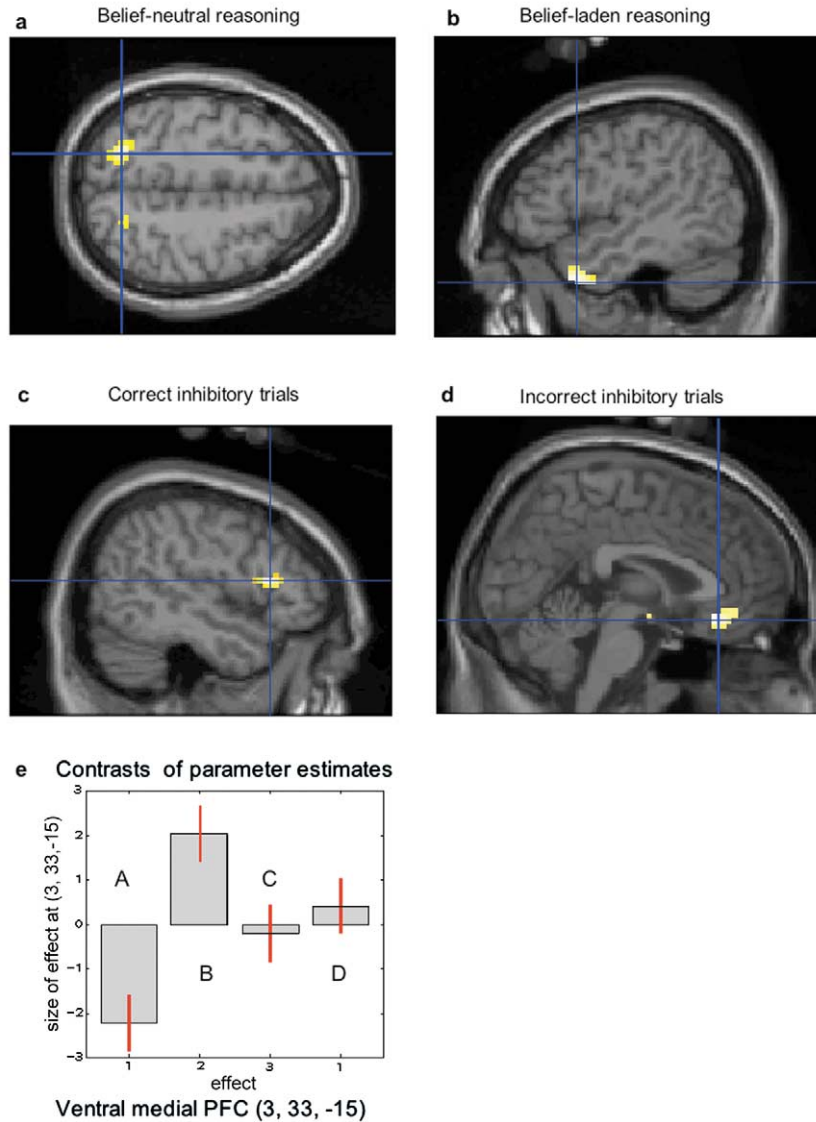
Fig. 2. A statistical parametric map (SPM) rendered into standard stereotactic space and superimposed on to transverse (a) and sagittal (b–d) sections of a magnetic resonance image (MRI) which is itself in standard space. (a) The direct comparison of belief-neutral reasoning with belief-laden reasoning resulted in activation of bilateral (L > R) superior parietal lobule (BA 7). (b) The reverse comparison of belief-laden reasoning with belief-neutral reasoning resulted in activation of the left pole of middle temporal gyrus (BA 21). (c) Within the inhibitory belief trials, a comparison of correct items with incorrect items revealed activation of right inferior prefrontal cortex (BA 45). (d) The reverse comparison revealed activation of VMPFC. (e) Condition specific parameter estimates for the above contrast show that the VMPFC is deactivated (with respect to facilitatory trials) during correct inhibitory trials and activated during incorrect inhibitory trials (A, correct inhibitory belief trials; B, incorrect inhibitory belief trials; C, correct facilitatory belief trials; D, incorrect facilitatory belief trials).

parietal system is known to be involved in the internal representation and manipulation of spatial information (Jonides, Smith, Koeppe, Awh, & Minoshima, 1993; Kosslyn, Koenig, Cave, Tang, & Gabrieli, 1989; Laeng, 1994) and is very similar to that reported for certain types of mathematical reasoning involving approximation of numerical quantities (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). This suggests that the neural structures involved in spatial processing are the basic building blocks for belief-neutral logical reasoning.

To alleviate concerns that the superior parietal lobule activation may be triggered by increased difficulty (rather than absence of meaningful content) it is worth noting that (i) only correct trials were used in the analysis and there were no differences in the RTs of these trials, (ii) the effect was also present for the inhibitory belief-laden trials vs. the belief-neutral trials, which were well matched for performance scores and RTs (though it does not survive correction), and (iii) a previous study of three-term spatial relations failed to associate increased parietal activation with task difficulty (Goel & Dolan, 2001b).

The present results extend our previous findings (Goel et al., 2000) in so far as logical arguments in the original study could be construed as meaningful vs. arbitrary, but also as concrete vs. abstract (because of the use of variables). In the present study we controlled for the latter by replacing variables with little known content words (matched for category to the belief-laden trials) and used subjects' belief ratings of each conclusion (determined by questionnaire after the scan) for the final categorization of trials. Thus, our arguments differed only with respect to meaningfulness (i.e. they were either belief-laden or belief-neutral). This suggests that the important factor in engagement of these two distinct neural systems is the engagement of a belief system rather than concrete or abstract content. How this dissociation maps onto the various dual mechanism theories in the reasoning literature remains an open question.

The critical novel contribution of the present study relates to the interaction of inhibitory belief-bias with reasoning processes. Within the inhibitory belief trials the prepotent response is associated with belief-bias. Correct responses (in inhibitory trials) indicate that subjects detected the conflict between their beliefs and the logical inference, inhibited the prepotent response associated with the belief-bias, and engaged the reasoning mechanism. Incorrect responses in such trials indicate that subjects failed to detect the conflict between their beliefs and the logical inference and/or inhibit the prepotent response associated with the belief-bias. Their response is biased by their beliefs. We conjecture that right prefrontal cortex involvement in correct response trials is critical in detecting and/or resolving the conflict between belief and logic. Such a role of the right lateral prefrontal cortex has been noted in a previous reasoning study (Goel et al., 2000) and in studies of maintenance of an intention in the face of conflict between action and sensory feedback (Fink et al., 1999). By contrast, the activation of VMPFC in incorrect trials highlights its role in non-logical, belief-based responses.[5]

These results and interpretation are consistent with several imaging and patient studies that have shown a dissociation between lateral/dorsolateral PFC structures and limbic system-related structures (Goel & Dolan, 2001a; Greene, Sommerville, Nystrom, Darley,

& Cohen, 2001; Hariri, Bookheimer, & Mazziotta, 2000; Koechlin, Corrado, Pietrini, & Grafman, 2000; Stuss & Levine, in press). Imaging studies have implicated the VMPFC in "guessing" or intuitive response tasks while lateral and dorsal prefrontal cortex has been activated in logical reasoning tasks (Elliott, Rees, & Dolan, 1999; Goel et al., 2000; Goel, Gold, Kapur, & Houle, 1997, 1998; Houde et al., 2000; Knauff, Mulack, Kassubek, Salih, & Greenlee, in press). Neuropsychological studies have demonstrated that while the rates of correct performance on arbitrary (belief-neutral) versions of the Wason Selection Task are very low for patients with ventral medial and dorsolateral lesions and normal controls, the VMPFC patients are the only ones who fail to show facilitation with the addition of familiar (belief-laden) content (Adolphs, Tranel, Bechara, Damasio, & Damasio, 1996). Other lesion studies have shown that in tasks where overt reasoning is facilitated by non-conscious response biasing, this facilitation is disrupted by VMPFC lesions (Bechara, Damasio, Tranel, & Damasio, 1997). In our task, belief-biasing in inhibitory trials leads to incorrect responses, and consistent with the above lesion studies engaged the VMPFC. Indeed clinical/anecdotal reports of VMPFC patients often describe them as being too rational and unable to integrate logical with affective responses (Damasio, 1994).

In conclusion, the present results indicate that the two dissociable systems we described previously (Goel et al., 2000) are selectively engaged by the presence (or absence) of belief-laden content rather than simply concrete or abstract content. More importantly, within the context of reasoning involving inhibitory beliefs, we show that the crucial element in the modulation of reasoning by beliefs is the preferential engagement of VMPFC. Where the VMPFC is preferentially engaged, subjects are more likely to generate responses based upon their belief-biases. This contrasts with correct logical reasoning that requires relatively greater activation of lateral prefrontal cortex. The involvement of VMPFC and its strong associations with affective processing indicates that belief-bias effects in reasoning may be a special instance of the modulatory effect of emotion on cognition.

Acknowledgements

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