

# The Hippocampal System Mediates Logical Reasoning about Familiar Spatial Environments

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## Abstract

■ It has recently been shown that syllogistic reasoning engages two dissociable neural systems. Reasoning about familiar situations engages a frontal–temporal lobe system, whereas formally identical reasoning tasks involving unfamiliar situations recruit a frontal–parietal visuospatial network. These two systems may correspond to the “heuristic” and “formal” methods, respectively, postulated by cognitive theory. To determine if this dissociation generalizes to reasoning about transitive spatial relations, we studied 14 volunteers using event-related fMRI, as they reasoned about landmarks in familiar and unfamiliar environments. Our main finding is a task (reasoning and baseline) by spatial content (familiar and unfamiliar) interaction. Modulation of reasoning toward unfamiliar landmarks resulted in bilateral activation

of superior and inferior parietal lobules (BA 7, 40), dorsal superior frontal cortex (BA 6), and right superior and middle frontal gyri (BA 8), regions widely implicated in visuospatial processing. By contrast, modulation of the reasoning task toward familiar landmarks, engaged the right inferior/orbital frontal gyrus (BA 11/47), bilateral occipital (BA 18, 19), and temporal lobes. The temporal lobe activation included the right inferior temporal gyrus (BA 37), posterior hippocampus, and parahippocampal gyrus, regions implicated in spatial memory and navigation tasks. These results provide support for the generalization of dual mechanism theory to transitive reasoning and highlight the importance of the hippocampal system in reasoning about familiar spatial environments. ■

## INTRODUCTION

Logical reasoning—considered by many to be the basis of human rationality—is the cognitive activity of evaluating arguments. All arguments involve the claim that one or more propositions (the premises) provide some grounds for accepting another proposition (the conclusion). Deduction is an important form of reasoning involving explication of information implicit in the premises. Valid deductive arguments involve the claim that their premises provide absolute grounds for accepting the conclusion. For example, in the argument “All men are mortal; Socrates is a man; ∴ Socrates is mortal,” the conclusion follows of necessity from the premises. Furthermore, as long as the logical form is preserved, the argument will be valid, irrespective of content.

Consistent with a dual mechanism theory of reasoning (Evans & Over, 1996; Sloman, 1996; Goel, 1995; Newell, 1990; Cheng & Holyoak, 1985), it has been recently shown that reasoning with categorical syllogisms engages two dissociable brain systems. Reasoning involving meaningful, familiar material (e.g., “All dogs are pets; All poodles are dogs; ∴ All poodles are pets”) engages a left hemisphere temporal lobe system. By contrast, formally identical reasoning tasks involving meaningless,

unfamiliar material (e.g., “All P are B; All C are P; ∴ All C are B”) recruit a bilateral parietal system (Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2003). The two systems share common components in the bilateral basal ganglia nuclei, right cerebellum, bilateral fusiform gyri, and left prefrontal cortex.

We have hypothesized that the frontal–temporal system underwrites reasoning via situation-specific heuristic processes based on subjects’ background knowledge and experience (Goel, 2003, in press). Where no such heuristics are available (as in reasoning about unfamiliar situations), formal methods must be used to solve the problem. These formal methods may involve representing the argument in something akin to Venn diagrams or other form of spatial representation, resulting in activation of a frontal–parietal visuospatial system (Goel, 2003, in press).

Categorical syllogisms constitute a small subset of logic. It is unknown whether this dissociation is specific to categorical syllogisms or generalizes to other forms of logical reasoning. To determine if the dissociation generalizes to transitive relational reasoning, we scanned 14 right-handed normal subjects (7 men and 7 women) using event-related functional magnetic resonance imaging (fMRI) to index task-related neural activity, while they evaluated the validity of arguments involving three-term spatial relations in familiar and unfamiliar environments.<sup>1</sup>

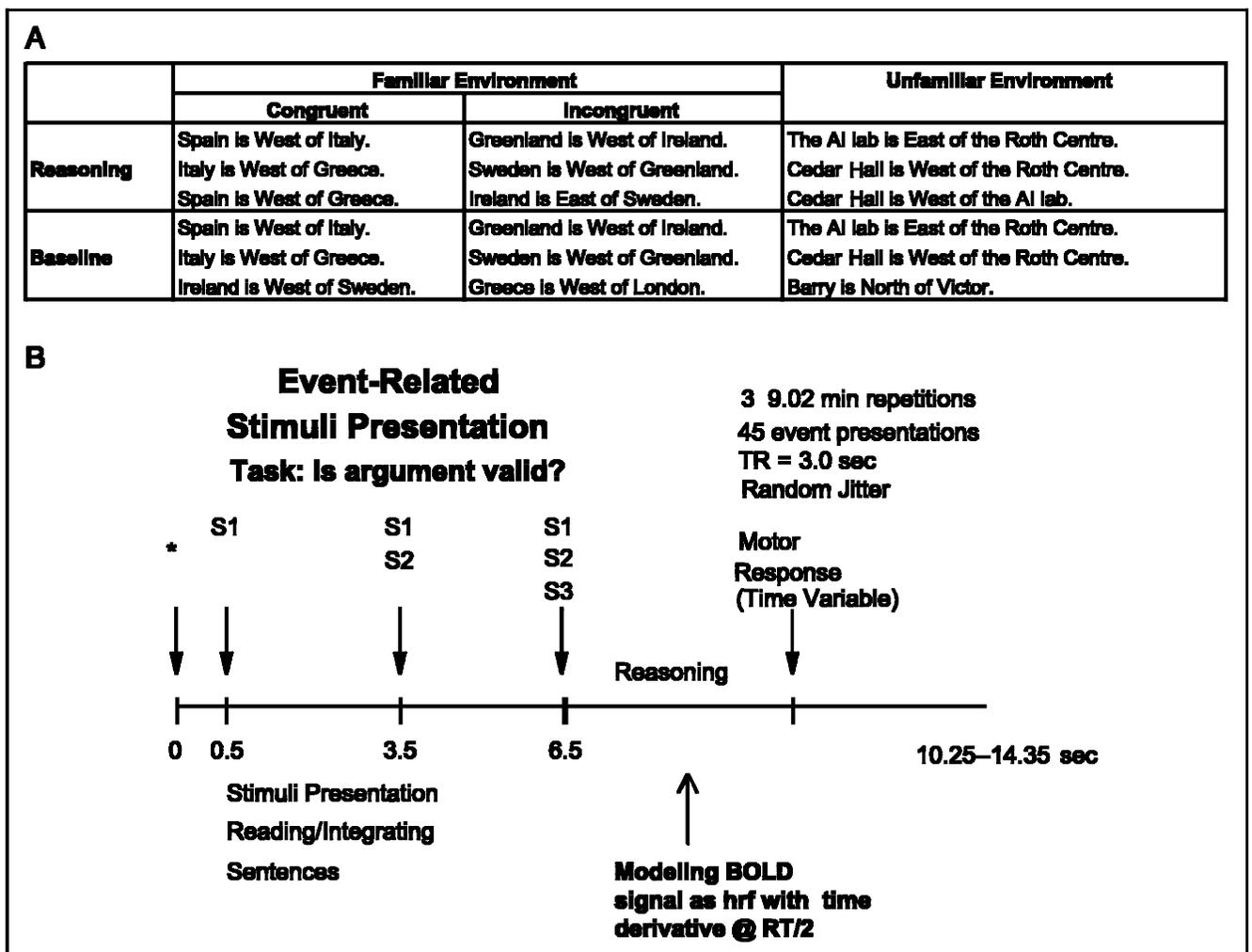
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Eighty spatial three-term relational arguments were organized into a factorial design (Figure 1A). The first factor was environmental familiarity in which half of the arguments (40) contained sentences such as “Paris is south of London; London is south of Edinburgh; ∴ Paris is south of Edinburgh” describing environments that subjects would be familiar with (as confirmed by a postscan questionnaire), while the other half (40) contained sentences such as “The AI lab is south of the Roth Centre; Roth Centre is south of Cedar Hall; ∴ AI lab is south of Cedar Hall” that subjects could not be familiar with because they describe a fictional unknown environment. The environmental landmarks included countries, cities, buildings, monuments, and so forth.<sup>2</sup>

The logical information in the familiar and unfamiliar conditions was identical. The following four logical forms were utilized: determinate consistent (e.g., A is ahead of B; C is ahead of A; ∴ C is ahead of B),

determinate inconsistent (e.g., A is ahead of B; C is ahead of A; ∴ C is behind B), indeterminate consistent (e.g., A is ahead of B; A is ahead of C; ∴ B is ahead of C), and indeterminate inconsistent (e.g., A is ahead of B; C is behind A; ∴ C is ahead of B). Indeterminate arguments have no valid conclusion while inconsistent arguments involve a transposition of the relation.

In arguments involving familiar environments, the conclusions—in addition to following or not following logically from the premises—were also true or false. Valid arguments with a true (or believable) conclusion (e.g., Paris is south of London; London is south of Edinburgh; ∴ Paris is south of Edinburgh) or invalid arguments with a false (or unbelievable) conclusion (e.g., Paris is north of London; Paris is north of Edinburgh; ∴ London is north of Edinburgh) are considered to be congruent trials. They are congruent (or facilitatory) because world knowledge and logical



**Figure 1.** (A) Overall design of study with sample stimuli. See text. (B) Stimuli from all conditions were presented randomly (unblocked) in an event-related design. An “\*” indicated the start of a trial at 0 sec. The sentences (grammatical, meaningful, and matched for length across conditions) appeared on the screen one at a time with the first sentence appearing at 500 msec, the second at 3500 msec, and the last sentence at 6500 msec, and remained on the screen until the end of the trial. The length of trials varied from 10.25 to 14.35 sec, leaving subjects 3.75–7.85 sec (after the presentation of the third sentence) to respond.

analysis lead to the same response. Invalid arguments with a true conclusion (e.g., Paris is south of London; Paris is south of Edinburgh; ∴ London is south of Edinburgh) or valid arguments with a false conclusion (e.g., Paris is north of London; London is north of Edinburgh; ∴ Paris is north of Edinburgh) are considered to be incongruent trials. They are incongruent (or inhibitory) because world knowledge and logical analysis lead to divergent responses. The task required subjects to attend to the logical form (ignoring the truth or falsity of the conclusion). The familiar environment trials were balanced for congruent and incongruent trials (20 of each type). Congruency and incongruency effects are much smaller for relational arguments than for categorical syllogisms (Roberts & Sykes, 2003).

The second factor was task. The first level was a reasoning condition consisting of the above 80 argument forms (balanced for validity and logical form). The second level (baseline condition) trials were generated by taking a subset of the above arguments and switching around the 3rd sentence such that the three sentences did not constitute arguments (e.g., AI lab is north of Roth Centre; AI lab is north of Cedar Hall; ∴ Tate Hall is north of Scott Library). Fifty-five baseline trials (18 congruent, 18 incongruent, and 19 unfamiliar) were used. All sentences were grammatical, meaningful, and matched for length (number of letters) across conditions.

## RESULTS

Behavioral scores are reported in Table 1. Subjects performed at 78.9% ( $SD = 15.4$ ) accuracy on the reasoning task compared to 99.56% ( $SD = 1.6$ ) in the baseline trials. There was no significant difference in accuracy scores for familiar and unfamiliar environment trials. Within the familiar environment reasoning condition, there was no significant difference in accuracy scores for facilitatory and inhibitory trials. Subjects took a mean of 3546 msec ( $SD = 695$ ) (after presentation of third sentence at 6500 msec) to respond to reasoning trials compared to 1487 msec ( $SD = 466$ ) for baseline trials. The mean reaction time (RT) for responding to familiar environment trials was 3473 msec ( $SD = 644$ )

**Table 1.** Behavioral Scores

	<i>Familiar Environment</i>		<i>Unfamiliar Environment</i>	
	Score (%)	RT (msec)	Score (%)	RT (msec)
Reasoning				
Incongruent	79.30	3609	77.17	3619
Congruent	81.93	3337		
Baseline	99.51	1488	99.61	1487

compared to 3619 msec ( $SD = 784$ ) for unfamiliar environment trials. The difference did not reach statistical significance. The mean RT for facilitatory trials was significantly less than the mean RTs for inhibitory trials,  $t(14) = 2.8, p < .05$ , and unfamiliar environment trials,  $t(14) = 2.98, p < .05$ .

The fMRI results are reported in Table 2. We began our analysis with a direct comparison of the familiar and unfamiliar environment reasoning conditions. The familiar environment versus unfamiliar environment reasoning comparison revealed activation in bilateral inferior and middle occipital gyri (BA 18, 19), right inferior temporal gyrus (BA 37), and bilateral (R > L) posterior hippocampi. The reverse comparison (unfamiliar landmark reasoning – familiar landmark reasoning) revealed activation in bilateral superior parietal lobule (BA 7) and bilateral (L > R) superior frontal gyrus (BA 6).

To verify that the involvement of these two dissociable systems was specific to the reasoning processes, and not simply due to the presence of familiar and unfamiliar spatial information in the arguments, we examined the task (reasoning and baseline) by spatial content (familiar and unfamiliar) interaction. It revealed a similar pattern of activation as the direct comparisons. Modulation of the reasoning task toward familiar landmarks [(familiar landmark reasoning – familiar landmark baseline) – (unfamiliar landmark reasoning – unfamiliar landmark baseline)] activated bilateral inferior and middle occipital gyri and lingual gyri (BA 18, 19) ( $-24, -78, -6; Z = 5.62; -21, -90, -6; Z = 5.57; 24, -75, -6; Z = 5.56; 21, -96, -6; Z = 5.04$ ) (Figure 2A), right inferior temporal gyrus (BA 37) ( $54, -54, -6; Z = 4.73$ ), left parahippocampal gyrus ( $-33, -24, -18; Z = 4.24; -36, -42, -12; Z = 4.72$ ) (Figure 2B), bilateral hippocampi ( $30, -30, -12; Z = 3.45; 30, -30, -12; Z = 3.30$ ) (Figure 2A and B), and right inferior/orbital frontal gyrus (BA 11/47) ( $21, 27, -12; Z = 3.66$ ) (Figure 2D).

The reverse modulation of reasoning toward unfamiliar landmarks [(unfamiliar landmark reasoning – unfamiliar landmark baseline) – (familiar landmark reasoning – familiar landmark baseline)] activated bilateral inferior parietal lobule (BA 40) ( $-60, -30, 42; Z = 4.81; 57, -39, 42; Z = 4.01$ ), bilateral superior parietal lobule (BA 7) ( $24, -48, 54; Z = 4.13; -24, -54, 48; Z = 4.19$ ), paracentral lobule (BA 4) ( $6, -33, 72; Z = 4.15$ ) (Figure 3A and C), bilateral superior frontal gyri (BA 6) ( $30, 6, 60; Z = 4.40; 24, 36, 36; Z = 3.78; -24, -15, 3, 60; Z = 4.51$ ) (Figure 3C), and right superior and middle frontal gyri (BA 8) ( $24, 36, 36; Z = 3.78$ ) (Figure 3D).

Consistent with these results, the simple effect of reasoning about unfamiliar environments (unfamiliar environment reasoning – unfamiliar environment baseline) activated bilateral occipital gyrus (BA 18, 19), bilateral superior parietal lobule (BA 7), left inferior parietal lobule (BA 40), left precentral gyrus (BA 4), left

**Table 2.** Areas of Activation

<i>Location (Brodmann's Area)</i>	<i>MNI Coordinates</i>			<i>Z Score</i>
	<i>X</i>	<i>Y</i>	<i>Z</i>	
<i>Familiar Environment Reasoning – Unfamiliar Environment Reasoning</i>				
Right inferior occipital gyrus (BA 18)	27	–90	–6	5.10
Left inferior occipital gyrus (BA 18)	–21	–93	–6	5.00
Right middle occipital gyrus (BA 18/19)	27	–75	–6	5.01
Left middle occipital gyrus (BA 18/19)	–24	–78	–6	4.75
Right inferior temporal gyrus (BA 37)	54	–57	–6	4.82
Right posterior hippocampus	27	–30	–12	5.25
Left posterior hippocampus	–27	–27	–6	3.31
<i>Unfamiliar Environment Reasoning – Familiar Environment Reasoning</i>				
Right superior parietal lobule	12	–54	66	4.79
Left superior parietal lobule	–9	–51	66	4.96
Right superior frontal gyrus (BA 6)	27	0	48	4.52
Left superior frontal gyrus (BA 6)	–27	–12	54	4.87
<i>Interaction: [(Unfamiliar Environment Reasoning – Unfamiliar Environment Baseline) – (Familiar Environment Reasoning – Familiar Environment Baseline)]</i>				
Right inferior parietal lobule (BA 40)	57	–39	42	4.01
Left inferior parietal lobule (BA 40)	–60	–30	42	4.81
Right superior parietal lobule (BA 7)	24	–48	54	4.13
Left superior parietal lobule (BA 7)	–24	–54	48	4.19
Right paracentral lobule (BA 4)	6	–33	72	4.15
Right superior frontal gyri (BA 6)	30	6	60	4.40
Left superior frontal gyri (BA 6)	–24	3	60	4.51
Right superior and middle frontal gyri (BA 8)	24	36	36	3.78
<i>Interaction: [(Familiar Environment Reasoning – Familiar Environment Baseline) – (Unfamiliar Environment Reasoning – Unfamiliar Environment Baseline)]</i>				
Left occipital and lingual gyri (BA 18, 17)	–24	–78	–6	5.62
Left occipital and lingual gyri (BA 18, 17)	–21	–90	–6	5.57
Right occipital and lingual gyri (BA 18, 17)	24	–75	–6	5.56
Right occipital and lingual gyri (BA 18, 17)	21	–96	–6	5.04
Right inferior temporal gyrus	54	–54	–6	4.73
Left parahippocampal gyrus	–33	–24	–18	4.24
Left parahippocampal gyrus	–36	–42	–12	4.72
Right hippocampus	30	–30	–12	3.45
Left hippocampus	–30	–27	–12	3.30
Right frontal inferior/orbital gyrus (BA 11/47)	21	27	–12	3.88

**Table 2.** (continued)

Location (Brodmann's Area)	MNI Coordinates			Z Score
	X	Y	Z	
<i>Unfamiliar Environment Reasoning – Unfamiliar Environment Baseline</i>				
Left occipital gyrus (BA 18, 19)	–36	–90	24	4.20
Right occipital gyrus (BA 18, 19)	30	–90	24	4.09
Left superior parietal lobule (BA 7)	–12	–69	66	4.92
Left superior parietal lobule (BA 7)	–24	–72	60	4.80
Right superior parietal lobule (BA 7)	12	–81	54	4.73
Left inferior parietal lobule (BA 40)	48	–45	60	3.85
Left precentral gyrus (BA 4)	–54	–12	42	4.36
Left superior frontal gyrus (BA 6)	–21	6	72	4.82
Left putamen	–24	–3	0	4.25
Right putamen	24	0	0	3.10
Left middle frontal gyrus (BA 9)	–39	45	30	3.74
Left middle frontal gyrus (BA 46)	–51	24	36	3.77
Left frontal orbital gyrus (BA 11)	–24	30	–6	3.82
Right frontal inferior/orbital gyrus (BA 11/47)	21	27	–12	3.66
<i>Familiar Environment Reasoning – Familiar Environment Baseline</i>				
Right inferior occipital gyrus (BA 18)	27	–84	0	3.31
Left thalamus and subthalamus	12	–12	–6	4.24
Right posterior hippocampus	24	–33	–6	4.03
Left posterior hippocampus	–24	–33	–6	3.60
Right superior temporal sulcus (BA 21/22)	45	3	–24	3.35
<i>Incongruent – Congruent</i>				
Left inferior occipital gyrus (BA 18)	–21	–99	0	4.04
Left lingual gyrus (BA 18)	–15	–66	0	3.91
Right Parahippocampal gyrus	36	–24	–18	3.99
Right frontal orbital gyrus (BA 11)	30	33	–12	3.96

superior frontal gyrus (BA 6), bilateral (L > R) putamen, left middle frontal gyrus (BA 46, 9), left frontal orbital gyrus (BA 11), and right inferior/orbital frontal gyrus (BA 11/47). The simple effect of reasoning about familiar environments (familiar environment reasoning – familiar environment baseline) activated left thalamus and subthalamus, bilateral (R > L) posterior hippocampus, right superior temporal sulcus (BA 21/22), and right inferior occipital gyrus (BA 18).

Within the familiar landmark reasoning trials we compared the incongruent (inhibitory) trials with the congruent (facilitatory) trials (incongruent reasoning –

congruent reasoning). This revealed activation in the left occipital and lingual gyri (BA 18) (Figure 4A), right parahippocampal gyrus (Figure 4C), and right orbital frontal gyrus (BA 11) (Figure 4B). The reverse comparison did not reveal any significant activation.

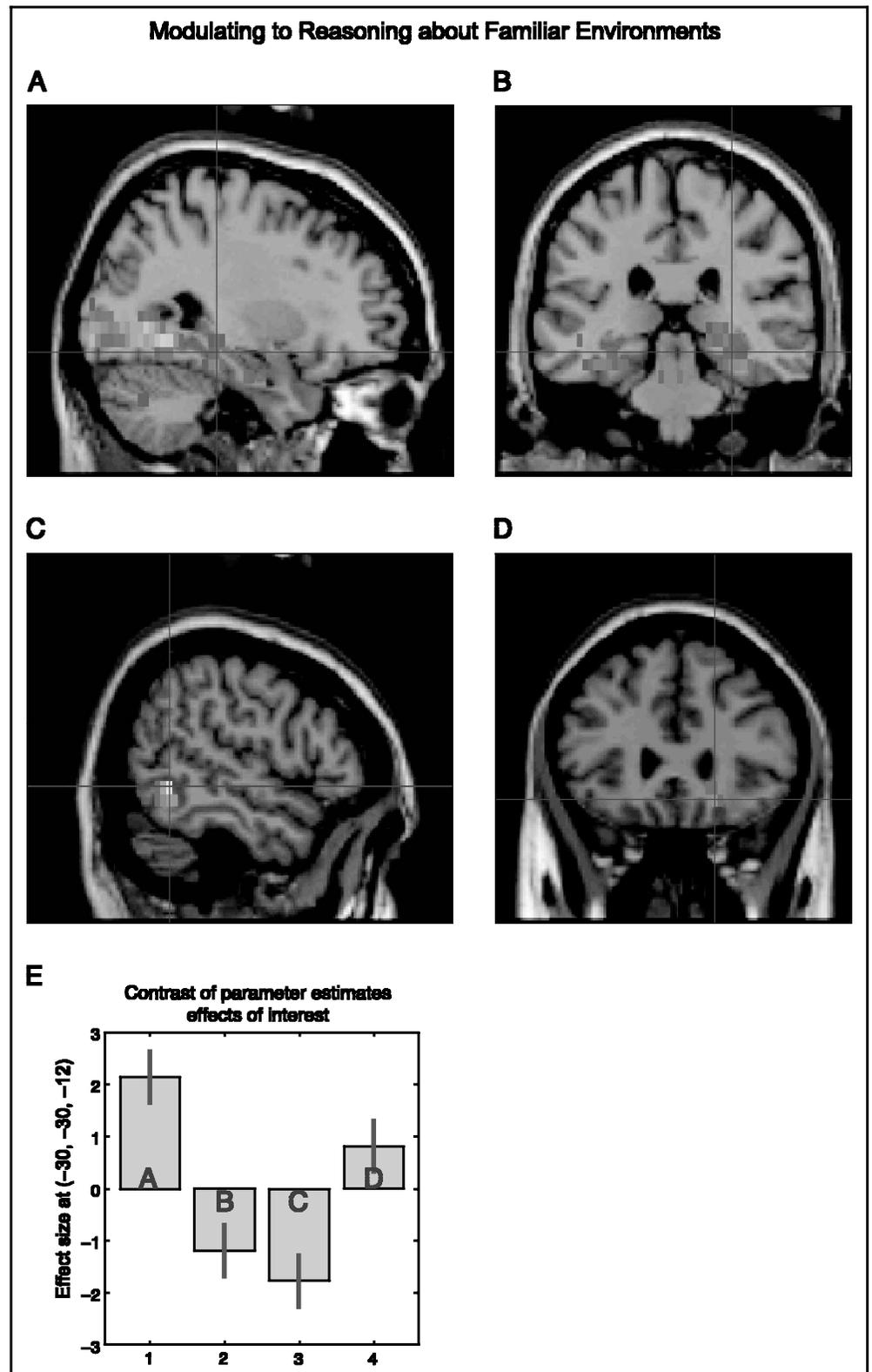
## DISCUSSION

The results show a differential pattern of neural activation during reasoning about familiar and unfamiliar spatial environments. Reasoning about unfamiliar environmental landmarks activated a bilateral parietal and

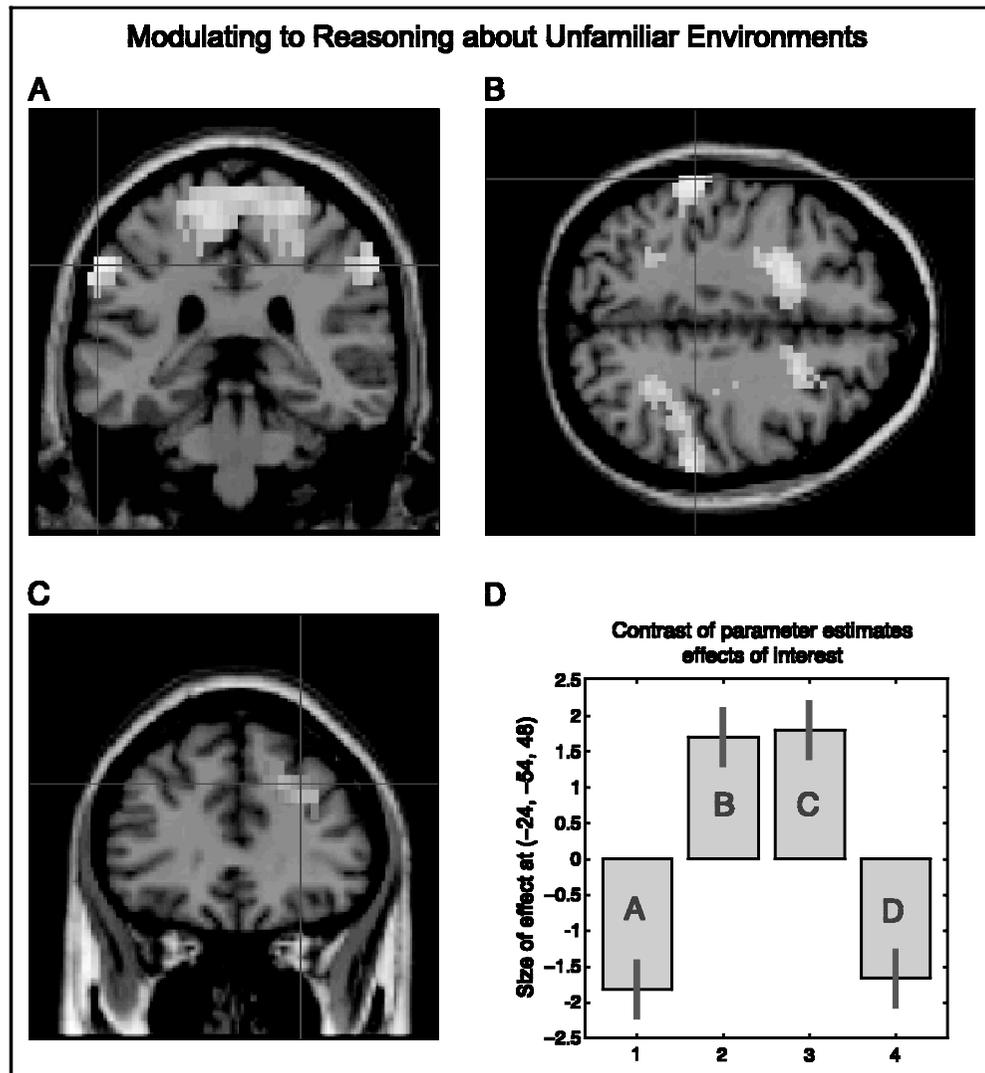
frontal system known to be involved in the internal representation and manipulation of spatial information (Nobre et al., 1997; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Corbetta, Miezin, Shulman, &

Petersen, 1993), including the manipulation of allocentric spatial relations (e.g., up, left, front, down, right, and back) (Mellet et al., 1996) such as found in our reasoning task. This network also subserves spatial working mem-

**Figure 2.** An SPM rendered into standard stereotactic space and superimposed on to sagittal (A,C) and coronal (B,D) sections of a magnetic resonance image, which is itself in standard space. The modulation of reasoning, toward familiar landmarks [(familiar landmark reasoning – familiar landmark baseline) – (unfamiliar landmark reasoning – unfamiliar landmark baseline)], activates (A and B) bilateral inferior and middle occipital gyri and lingual gyri (BA 18, 19) ( $-24, -78, -6; Z = 5.62; -21, -90, -6; Z = 5.57; 24, -75, -6; Z = 5.56; 21, -96, -6; Z = 5.04$ ), left parahippocampal gyrus ( $-33, -24, -18; Z = 4.24; -36, -42, -12; Z = 4.72$ ), and bilateral hippocampi ( $30, -30, -12; Z = 3.45; 30, -30, -12; Z = 3.30$ ), (C) right inferior temporal gyrus (BA 37) ( $54, -54, -6; Z = 4.73$ ), and (D) right inferior/orbital frontal gyrus (BA 11/47) ( $21, 27, -12; Z = 3.66$ ). (E) Graph of parameter estimates shows reciprocal response of right posterior hippocampus ( $-30, -30, -12$ ) to reasoning about landmarks in familiar and unfamiliar environments (A = familiar environment reasoning, B = familiar environment baseline, C = unfamiliar environment reasoning, D = unfamiliar environment baseline).



**Figure 3.** An SPM rendered into standard stereotactic space and superimposed on to coronal (A,C) and transverse (B) sections of a magnetic resonance image, which is itself in standard space. The modulation of reasoning, toward unfamiliar landmarks [(unfamiliar landmark reasoning – unfamiliar landmark baseline) – (familiar landmark reasoning – familiar landmark baseline)], (A and B) activated bilateral inferior parietal lobule (BA 40) ( $-60, -30, 42; Z = 4.81; 57, -39, 42; Z = 4.01$ ), bilateral superior parietal lobule (BA 7) ( $24, -48, 54; Z = 4.13$  and  $-24, -54, 48; Z = 4.19$ ), paracentral lobule (BA 4) ( $6, -33, 72; Z = 4.15$ ), and bilateral superior frontal gyri (BA 6) ( $30, 6, 60; Z = 4.40; 24, 36, 36; Z = 3.78; -24, -15, 3, 60; Z = 4.51$ ), and (C) right superior and middle frontal gyri (BA 8) ( $24, 36, 36; Z = 3.78$ ). (D) Graph of parameter estimates shows reciprocal response of superior parietal lobule ( $-24, -54, 48$ ) to reasoning about landmarks in familiar and unfamiliar environments (A = familiar environment reasoning, B = familiar environment baseline, C = unfamiliar environment reasoning, D = unfamiliar environment baseline).



ory rehearsal and manipulation processes (Jonides et al., 1998; Smith & Jonides, 1998) and is very similar to the network reported for transitive inference involving geometrical shapes (Acuna, Eliassen, Donoghue, & Sanes, 2002). Our interpretation is that in the absence of relevant world knowledge, the neural structures involved in visuospatial processing are the basic building blocks for reasoning. This is consistent with the view that reasoning in such situations involves the manipulation of some form of Venn diagrams or spatial mental models (Johnson-Laird, 1994).

By contrast, reasoning about familiar environmental landmarks activated the bilateral occipital and temporal regions (with activation in left occipital and right parahippocampal gyrus being greater in the incongruent trials than the congruent trials). Occipital activation in the secondary visual cortex may reflect a greater degree of visual encoding in the familiar landmark condition, whereas activation of BA 37—often found in situations involving violation of expectations (Goel & Dolan,

2001a)—may reflect decoding of premises that conflict with geographic knowledge (e.g., London is south of Cairo). More critically, in keeping with its category-specific organization, temporal lobe contributions to logical reasoning are anatomically specific to the nature of the content involved in the reasoning task. Arguments about familiar properties of people, animals, and artifacts implicate left lateral anterior regions (BA 21/22) (Goel et al., 2000; Goel & Dolan, 2003). The present arguments about familiar environments/landmarks activated bilateral temporal lobe regions, including posterior ( $R > L$ ) hippocampus and parahippocampal gyrus, known to be involved in episodic memory and novelty detection (Schacter & Wagner, 1999; Strange, Fletcher, Henson, Friston, & Dolan, 1999; Dolan & Fletcher, 1997), spatial memory (Biegler, McGregor, Krebs, & Healy, 2001; Bohbot et al., 1998; Smith & Milner, 1981), particularly memory involving geographic and object landmarks (Gorno-Tempini & Price, 2001; Maguire, Frith, Burgess, Donnett, & O’Keefe, 1998; Maguire,

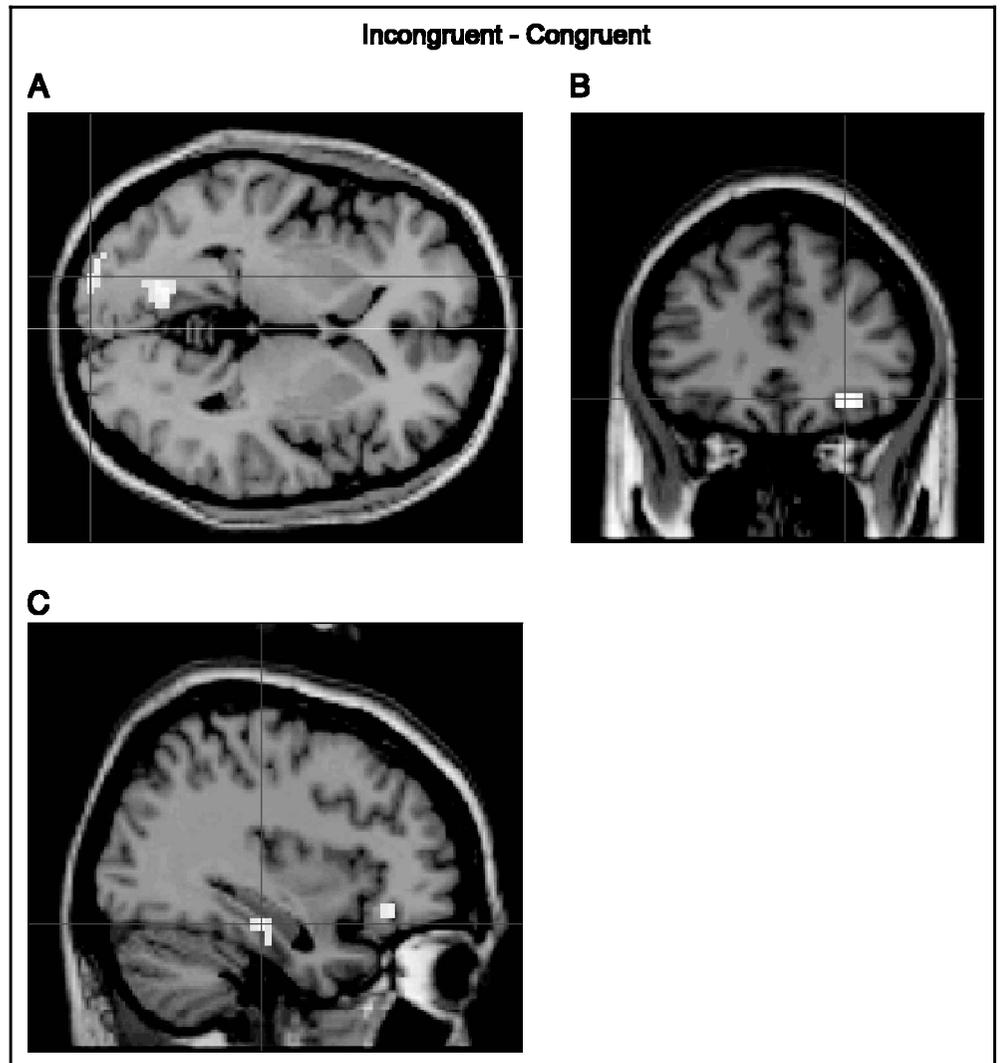
Frith, & Cipolotti, 2001) and navigation through familiar spatial environments (Maguire, Frackowiak, & Frith, 1997). Our claim is that reasoning about familiar environments utilizes situation-specific heuristic (i.e., relevant world knowledge), and in the case of spatial reasoning, is underwritten by the hippocampal system.

Both of the systems we are implicating in reasoning about familiar and unfamiliar environments are well known to be involved in the representation of spatial information. Thus, one alternate interpretation of our results is that the dissociation we have found has nothing to do with reasoning per se but is simply a function of the presence of familiar and unfamiliar spatial information. A simple direct comparison of reasoning about familiar and unfamiliar environments may well lead to this interpretation. However, our claim rests on a task (reasoning and baseline) by spatial content (familiar and unfamiliar) interaction. In the interaction analyses, the familiarity-specific baselines control for the presence of familiar and unfamiliar spatial information. The parameter estimates in Figure 2E show that the

temporal lobe system—in addition to responding reciprocally to familiar and unfamiliar reasoning trials—responds to the familiar reasoning trials but not to the familiar baseline trials, and its response to unfamiliar baseline trials is greater than its response to familiar baseline trials. The parietal system also responds reciprocally to familiar and unfamiliar reasoning trials, but with the reverse pattern (Figure 3D). It is activated by the unfamiliar reasoning trials but not the unfamiliar baseline trials, and its response to familiar baseline trials is greater than its response to unfamiliar baseline trials. This pattern of response is strong evidence that these regions are not merely being activated by the presence of spatial information but are actually engaged in the reasoning process.

Consistent with previous studies (Acuna et al., 2002; Goel et al., 2000; Goel & Dolan, 2001b; Goel & Dolan, 2003; Houde et al., 2000), we also found the bilateral prefrontal cortex mediates reasoning about unfamiliar situations, whereas the right lateral/orbital prefrontal cortex is needed to resolve/navigate the belief-logic

**Figure 4.** An SPM rendered into standard stereotactic space and superimposed on to transverse (A), coronal (B), and sagittal (C) sections of a magnetic resonance image, which is itself in standard space. The incongruent versus congruent trials activate (A) left inferior occipital and lingual gyrus (BA 18) (-21, 99, 0;  $Z = 4.04$ ; -15, -66, 0;  $Z = 3.91$ ), (B) right frontal orbital gyrus (BA 11) (30, 33, -12;  $Z = 3.96$ ), and (C) right parahippocampal gyrus (36, -24, -18;  $Z = 3.96$ ).



conflict that occurs in incongruent reasoning trials. One surprising finding was the absence of activation in the left lateral prefrontal cortex during familiar environment reasoning trials. This may result from a lack of power in our design or reflect a difference in how the brain handles spatial and nonspatial knowledge.

In terms of a theory of reasoning, what is critical about our results is the dissociation between reasoning about familiar and unfamiliar environments. The major cognitive theories of logical reasoning (mental logic and mental models theories) do not predict this dissociation (Johnson-Laird, 1994; Rips, 1994; Braine, 1978; Henle, 1962). Our results, along with previous studies (Goel et al., 2000; Goel & Dolan, 2003), question the sufficiency of these cognitive theories and lead us to the position that there is no “logic” module. Brain systems for reasoning are dynamically configured as a function of the relationship between organism and the reasoning material. The current results emphasize the role of subjects’ beliefs/knowledge about the reasoning material in configuring neural systems of reasoning.

Specifically, our findings indicate that the dissociation reported for categorical syllogisms generalizes across transitive reasoning and helps to clarify the different roles of the parietal and temporal lobe systems. Given that bilateral parietal activation has been reported in no-content categorical syllogisms (Goel et al., 2000; Goel & Dolan, 2003), no-content three-term spatial relations, and unfamiliar (belief-neutral) content three-term spatial relations (Acuna et al., 2002; Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002; Goel & Dolan, 2001b) indicates that it is responding to unfamiliar situations (i.e., situations void of meaningful associations for the subject) and is part of the formal methods reasoning system. By contrast, the temporal lobe is recruited in the service of logical reasoning by the presence of familiar/meaningful content and its response is situation specific, suggesting it is part of the heuristic methods reasoning system. In the case of categorical (nonspatial) syllogisms, the left lateral anterior temporal lobe is activated while in the case of transitive inferences about familiar spatial environments, reasoning is mediated by bilateral (R > L) posterior hippocampus and parahippocampal gyrus, the same structures that underwrite spatial memory and navigation tasks.

## METHODS

### Subjects

Fourteen right-handed normal subjects (7 men and 7 women), with a mean age of 26.6 years ( $SD = 4.5$ ) and mean education level of 16.1 years ( $SD = 2.1$ ), volunteered to participate in the study. All subjects gave informed consent and the study was approved by the Institutional Review Board.

### Stimuli Presentation

Stimuli from all conditions were presented randomly (unblocked) in an event-related design (see Figure 1B). 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) irrespective of the truth and falsity of the conclusion. Subjects responded by pressing a button on a keypad after the appearance of the last sentence. In (baseline) trials, where the first two sentences were related, subjects would need to begin to integrate the premises and construct a representation of the problem, but when the third, unrelated, sentence appeared, they could immediately disengage the task and respond “no.” In (reasoning) trials where the three sentences constituted an argument, subjects would need to continue with the reasoning component of the task after the presentation of the third sentence. The difference between completing the reasoning task and disengaging after the presentation of the third sentence will isolate the reasoning components of interest. 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.

### fMRI Scanning Technique

Imaging experiments were performed using a General Electric 3.0-T whole-body magnetic resonance scanner. A sagittal localizer was performed, followed by the acquisition of a  $256 \times 256 \times 124$  3-D SPGR volume with a voxel size of  $0.9375 \times 0.9375 \times 1.5$  mm. Functional (fMRI) volumes were acquired using echo planar imaging with a TR of 3000 msec and a TE of 40 msec. Each brain volume was obtained using two excitation pulses and consisted of 22 interleaved slices that were 6 mm thick with no gap. The in-plane matrix was  $64 \times 64$ , with a voxel dimension of  $3.75 \times 3.75$  mm. 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 3.0 sec/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  $12,000 \pm 1500$  msec (TR) with a random jitter. Trials thus varied from 10.50 to 13.50 sec. There were 45 event presentations during a session for a total of 135 over the three sessions. Each session lasted 9.02 min.

### Data Analysis

Data were analyzed using Statistical Parametric Mapping (SPM '99) (Friston et al., 1995). All volumes in a session

were spatially realigned to the first volume of the session and temporally realigned to the AC–PC slice to account for different sampling times of different slices. All subjects had head movement less than 3 mm. A mean image created from the realigned volumes was coregistered with the structural T1 volume. The structural volumes were then spatially normalized to the Montreal Neurological Institute brain template (Evans et al., 1993) using nonlinear basis functions (Ashburner & Friston, 1999). The derived spatial transformation was then applied to the realigned T2\* volumes, which were finally spatially smoothed with a 6-mm full width at half maximum isotropic Gaussian kernel (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 120 sec, 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.

Condition effects at each voxel were estimated according to the general linear model and regionally specific effects compared using linear contrasts. Each contrast produced an SPM of the *t* statistic for each voxel, which was subsequently transformed to a unit normal *Z* distribution. The activations reported survived a voxel-level intensity threshold of  $p < .05$  using a random effect model (corrected for multiple comparisons using false discovery rate) (Genovese, Lazar, & Nichols, 2002). Given the principle of anatomical symmetry, where an anatomical structure is 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 modeled as hemodynamic response function with a time derivative at the midway point between the presentation of the third sentence and the motor response, on a trial by trial, subject by subject basis. The presentation of all three sentences, along with the motor response were modeled as events of no interest.

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The data reported in this experiment have been deposited in the fMRI Data Center (<http://www.fmridc.org>). The accession number is 2-2003-114CA.

## Notes

1. Transitivity is the logical property of transferability such that, the relation A has to B and B to C, transfers from A to C (A = B; B = C; A = C). The transitivity relation is a basic cornerstone of logic.

2. In using the term *environmental familiarity*, we are not implying subjects are navigating a 3-D space at the first person level. They are accessing semantic knowledge—derived from maps, books, or personal experience—of countries, cities, buildings, landmarks, and so forth.

## REFERENCES

- Acuna, B. D., Eliassen, J. C., Donoghue, J. P., & Sanes, J. N. (2002). Frontal and parietal lobe activation during transitive inference in humans. *Cerebral Cortex*, *12*, 1312–1321.
- Ashburner, J., & Friston, K. J. (1999). Nonlinear spatial normalization using basis functions. *Human Brain Mapping*, *7*, 254–266.
- Biegler, R., McGregor, A., Krebs, J. R., & Healy, S. D. (2001). A larger hippocampus is associated with longer-lasting spatial memory. *Proceedings of the National Academy of Sciences, U.S.A.*, *98*, 6941–6944.
- Bohbot, V. D., Kalina, M., Stepankova, K., Spackova, N., Petrides, M., & Nadel, L. (1998). Spatial memory deficits in patients with lesions to the right hippocampus and to the right parahippocampal cortex. *Neuropsychologia*, *36*, 1217–1238.
- Braine, M. D. S. (1978). On the relation between the natural logic of reasoning and standard logic. *Psychological Review*, *85*, 1–21.
- Cheng, P. W., & Holyoak, K. J. (1985). Pragmatic reasoning schemas. *Cognitive Psychology*, *17*, 391–416.
- Corbetta, M., Miezin, F. M., Dobmeyer, S., Shulman, G. L., & Petersen, S. E. (1991). Selective and divided attention during visual discriminations of shape, color, and speed: Functional anatomy by positron emission tomography. *Journal of Neuroscience*, *11*, 2383–2402.
- Corbetta, M., Miezin, F. M., Shulman, G. L., & Petersen, S. E. (1993). A PET study of visuospatial attention. *Journal of Neuroscience*, *13*, 1202–1226.
- Dolan, R. J., & Fletcher, P. C. (1997). Dissociating prefrontal and hippocampal function in episodic memory encoding. *Nature*, *388*, 582–585.
- Evans, A. C., Collins, D. L., Mills, S. R., Brown, E. D., Kelly, R. L., & Peters, T. M. (1993). 3D statistical neuroanatomical models from 305 MRI volumes. *Proceedings of the IEEE Nuclear Science Symposium and Medical Imaging Conference*, 1813–1817.
- Evans, J. St. B. T., & Over, D. E. (1996). *Rationality and reasoning*. New York: Psychology Press.
- Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. B., Frith, C. D., & Frackowiak, R. S. J. (1995). Statistical parametric maps in functional imaging: A general approach. *Human Brain Mapping*, *2*, 189–210.
- Genovese, C. R., Lazar, N. A., & Nichols, T. (2002). Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *Neuroimage*, *15*, 870–878.
- Goel, V. (1995). *Sketches of thought*. Cambridge: MIT Press.
- Goel, V. (2003). Evidence for dual neural pathways for syllogistic reasoning. *Psychologica*, *32*, 301–309.
- Goel, V. (in press). Cognitive neuroscience of deductive reasoning. In K. Holyoak (Ed.), *Cambridge handbook of thinking and reasoning*. Cambridge: Cambridge University Press.
- Goel, V., Buchel, C., Frith, C., & Dolan, R. J. (2000). Dissociation of mechanisms underlying syllogistic reasoning. *Neuroimage*, *12*, 504–514.
- Goel, V., & Dolan, R. J. (2001a). Functional neuroanatomy of humor: Segregating cognitive and affective components. *Nature Neuroscience*, *4*, 237–238.

- Goel, V., & Dolan, R. J. (2001b). Functional neuroanatomy of three-term relational reasoning. *Neuropsychologia*, *39*, 901–909.
- Goel, V., & Dolan, R. J. (2003). Explaining modulation of reasoning by belief. *Cognition*, *87*, B11–B22.
- Gorno-Tempini, M. L., & Price, C. J. (2001). Identification of famous faces and buildings: A functional neuroimaging study of semantically unique items. *Brain*, *124*, 2087–2097.
- Henle, M. (1962). On the relation between logic and thinking. *Psychological Review*, *69*, 366–378.
- Houde, O., Zago, L., Mellet, E., Moutier, S., Pineau, A., Mazoyer, B., & Tzourio-Mazoyer, N. (2000). Shifting from the perceptual brain to the logical brain: The neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience*, *12*, 721–728.
- Johnson-Laird, P. N. (1994). Mental models, deductive reasoning, and the brain. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 999–1008). Cambridge: MIT Press.
- Jonides, J., Schumacher, E. H., Smith, E. E., Koeppe, R. A., Awh, E., Reuter-Lorenz, P. A., Marshuetz, C., & Willis, C. R. (1998). The role of parietal cortex in verbal working memory. *Journal of Neuroscience*, *18*, 5026–5034.
- Knauff, M., Mulack, T., Kassubek, J., Salih, H. R., & Greenlee, M. W. (2002). Spatial imagery in deductive reasoning: A functional MRI study. *Brain Research: Cognitive Brain Research*, *13*, 203–212.
- Maguire, E. A., Frackowiak, R. S., & Frith, C. D. (1997). Recalling routes around London: Activation of the right hippocampus in taxi drivers. *Journal of Neuroscience*, *17*, 7103–7110.
- Maguire, E. A., Frith, C. D., Burgess, N., Donnett, J. G., & O'Keefe, J. (1998). Knowing where things are: parahippocampal involvement in encoding object locations in virtual large-scale space. *Journal of Cognitive Neuroscience*, *10*, 61–76.
- Maguire, E. A., Frith, C. D., & Cipolotti, L. (2001). Distinct neural systems for the encoding and recognition of topography and faces. *Neuroimage*, *13*, 743–750.
- Mellet, E., Tzourio, N., Crivello, F., Joliot, M., Denis, M., & Mazoyer, D. (1996). Functional anatomy of spatial mental imagery generated from verbal instructions. *Journal of Neuroscience*, *16*, 6504–6512.
- Newell, A. (1990). *Unified theories of cognition*. Cambridge: Harvard University Press.
- Nobre, A. C., Sebestyen, G. N., Gitelman, D. R., Mesulam, M. M., Frackowiak, R. S., & Frith, C. D. (1997). Functional localization of the system for visuospatial attention using positron emission tomography. *Brain*, *120*, 515–533.
- Rips, L. J. (1994). *The psychology of proof: Deductive reasoning in human thinking*. Cambridge: MIT Press.
- Roberts, M. J., & Sykes, E. D. (2003). Belief bias and relational reasoning. *Quarterly Journal of Experimental Psychology A*, *56*, 131–153.
- Schacter, D. L., & Wagner, A. D. (1999). Medial temporal lobe activations in fmri and pet studies of episodic encoding and retrieval. *Hippocampus*, *9*, 7–24.
- Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, *119*, 3–22.
- Smith, E. E., & Jonides, J. (1998). Neuroimaging analyses of human working memory. *Proceedings of the National Academy of Sciences, U.S.A.*, *95*, 12061–12068.
- Smith, M. L., & Milner, B. (1981). The role of the right hippocampus in the recall of spatial location. *Neuropsychologia*, *19*, 781–793.
- Strange, B. A., Fletcher, P. C., Henson, R. N., Friston, K. J., & Dolan, R. J. (1999). Segregating the functions of human hippocampus. *Proceedings of the National Academy of Sciences, U.S.A.*, *96*, 4034–4039.
- Worsley, K. J., & Friston, K. J. (1995). Analysis of fMRI time-series revisited—Again. *Neuroimage*, *2*, 173–181.