

# Neuroanatomical Correlates of Human Reasoning

Vinod Goel and Brian Gold

York University

Shitij Kapur

University of Toronto and Rotman Research Institute of Baycrest Centre

Sylvain Houle

University of Toronto

## Abstract

■ One of the important questions cognitive theories of reasoning must address is whether logical reasoning is inherently sentential or spatial. A sentential model would exploit nonspatial (linguistic) properties of representations whereas a spatial model would exploit spatial properties of representations. In general terms, the linguistic hypothesis predicts that the language processing regions underwrite human reasoning processes, and the spatial hypothesis suggests that the neural structures for perception and motor control contribute the basic representational building blocks used for high-level logical and linguistic reasoning. We carried out a [ $^{15}\text{O}$ ]  $\text{H}_2\text{O}$  PET imaging study to address this issue.

Twelve normal volunteers performed three types of deductive reasoning tasks (categorical syllogisms, three-term spatial relational items, and three-term nonspatial relational items) while their regional cerebral blood flow pattern was recorded using [ $^{15}\text{O}$ ]  $\text{H}_2\text{O}$  PET imaging. In the control condition subjects

semantically comprehended sets of three sentences. In the deductive reasoning conditions subjects determined whether the third sentence was *entailed by* the first two sentences.

The areas of activation in each reasoning condition were confined to the left hemisphere and were similar to each other and to activation reported in previous studies. They included the left inferior frontal gyrus (Brodmann areas 45, 47), a portion of the left middle frontal gyrus (Brodmann area 46), the left middle temporal gyrus (Brodmann areas 21, 22), a region of the left lateral inferior temporal gyrus and superior temporal gyrus (Brodmann areas 22, 37), and a portion of the left cingulate gyrus (Brodmann areas 32, 24). There was no significant right-hemisphere or parietal activation. These results are consistent with previous neuroimaging studies and raise questions about the level of involvement of classic spatial regions in reasoning about linguistically presented spatial relations. ■

## INTRODUCTION

Reasoning is the process of evaluating given information and reaching conclusions that are not explicitly stated. Here is literature's most celebrated reasoner (Conan Doyle's Sherlock Holmes in *Scandal in Bohemia*) impressing his friend Watson:

Then he stood before the fire, and looked me over in his singular introspective fashion.

"Wedlock suits you," he remarked. . . . And in practice again, I observe, You did not tell me that you intended to go into harness."

"Then how do you know?"

"I see it, I deduce it. How do I know that you have been getting yourself very wet lately, and that you have a most clumsy and careless servant girl?"

"It is simplicity itself," said he; "my eyes tell me that on the inside of your left shoe, just where the fire-

light strikes it, the leather is scored by six almost parallel cuts. Obviously they have been caused by someone who has very carelessly scraped round the edges of the sole in order to remove crusted mud from it. Hence, you see, my double deduction that you had been out in vile weather, and that you had a particularly malignant boot-slicking specimen of the London slavery. As to your practice, if a gentleman walks into my rooms, smelling of iodoform, with a black mark of nitrate of silver upon his right fore-finger, and a bulge on the side of his top-hat to show where he has secreted his stethoscope, I must be dull indeed if I do not pronounce him to be an active member of the medical profession."

More mundane examples are the following: Upon being told that George is a bachelor, I automatically infer that George is not married. Or upon learning that Linda will not come to my barbecue if it rains on Saturday, and

noting that it is indeed raining on Saturday, I do not set a place for her. Although not as impressive as Holmes' conclusions, our conclusions emerge in a straightforward way from the provided information.

Human reasoning—the ability to draw such conclusions—lies at the core of higher-level cognition and is an important area of study in cognitive science. On a first pass, the cognitive literature on reasoning can be divided into the study of deduction and induction. Deductive arguments can be evaluated for *validity*. Validity is a function of the relationship between premises and conclusion and involves the claim that the premises provide absolute grounds for accepting the conclusion. Arguments in which the premises provide only limited grounds for accepting the conclusion are broadly called inductive arguments. While invalid, inductive arguments can be evaluated for *plausibility* or *reasonableness*. But, whereas, validity can be reduced to a function of the logical structure of sentences and arguments, induction is a function of the content of the sentences and our knowledge of the world. It is usually a matter of knowing which properties generalize in the required manner and which do not.

The illustrations we began with provide examples of both argument types. Holmes' conclusions take us far beyond the given information, and despite Doyle's insistence, are not deductions, in the technical sense of the word. They are instances of induction. What Holmes observes does not provide absolute grounds for accepting the conclusion he draws. For example, it is plausible that the "six almost parallel cuts" on Watson's left shoe were "caused by someone who has very carelessly scraped round the edges of the sole in order to remove crusted mud from it." But it is equally plausible that someone was trying to scrape grease from the soles or that the shoe scraped against a sharp object while Watson was wearing it.

Our more mundane examples are instances of deduction. They do not take us beyond the given information. The conclusions are contained within the premises and are independent of the content of the sentences. For example, given the information that Linda will not come to my barbecue if it is raining, and it is indeed raining, the only possible conclusion is that Linda will not come. Furthermore, the same conclusion holds irrespective of whether the individual in question is Linda or Mary or whether the event in question is a barbecue or a dinner party.

Over the years a number of sophisticated cognitive and computational models of deductive reasoning have been developed (Evans, Newstead, & Byrne, 1993; Johnson-Laird, 1993, 1994; Newell, 1980, 1990; Polk & Newell, 1995). One important question these models have to address is whether logical reasoning is inherently sentential or spatial. A sentential model would exploit nonspatial (linguistic) properties of representations whereas a spatial model would exploit spatial properties

of representations. Sentential representations are associated with "mental logic" models (Braine, 1978; Rips, 1994). Spatial representations are typically associated with the mental model theory of reasoning (Bauer & Johnson-Laird, 1993; Johnson-Laird, 1994; Johnson-Laird & Byrne, 1991). Mental models do not have to be spatial, but insofar as structural relations are preserved in the mapping from world to model, arguments involving spatial relations will involve spatial encoding.

In general terms, the linguistic hypothesis predicts that the language processing regions underwrite human reasoning processes, and the spatial hypothesis suggests that the neural structures for perception and motor control contribute the basic representational building blocks used for high-level logic and linguistic reasoning. However, most of what we know about human reasoning is informed by behavioral data and computational considerations. Little is known about the neuroanatomical correlates of reasoning processes. This is of course not a criticism. Given the absence of robust animal models of reasoning, it is inevitable. But recent advances in vivo positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) techniques have made it possible to probe the neurophysiological basis of human reasoning. Such explorations allow us to map out the neuroanatomical correlates of reasoning processes. They also provide data points to inform the development of cognitive models.

Goel, Gold, Kapur, and Houle (1997) carried out a study to explore the neuroanatomical correlates of inductive and deductive reasoning using paradigms adopted from the cognitive reasoning literature. They had 10 normal volunteers perform deductive and inductive reasoning tasks while their regional cerebral blood flow (rCBF) pattern was recorded using the [<sup>15</sup>O] H<sub>2</sub>O PET imaging technique. Subjects were presented with arguments of the following type and asked to make judgments about validity and plausibility:<sup>1</sup>

1. All men are mortal; Socrates is a man  
∴ Socrates is mortal
2. If Socrates is a cat, he has 9 lives; Socrates is a cat  
∴ Socrates has 9 lives
3. Socrates is a cat, Socrates has 32 teeth  
∴ All cats have 32 teeth
4. Socrates is a cat; Socrates has a broken tooth  
∴ All cats have a broken tooth

The deduction condition resulted in activation of the left inferior frontal gyrus (Brodmann areas 45, 47) and a region of the left superior occipital gyrus (Brodmann area 19). The induction condition resulted in activation of a large area comprised of the left medial frontal gyrus, the left cingulate gyrus, and the left superior frontal gyrus (Brodmann areas 8, 9, 24, 32). Other frontal areas activated were the orbital aspect of the left inferior frontal gyrus (Brodmann area 47) and the left middle frontal gyrus (Brodmann area 10). The only nonfrontal

areas activated were a region of the left superior occipital gyrus (Brodmann area 19) and a small region of the lateral inferior temporal gyrus (Brodmann area 20). When the deduction condition was subtracted from the induction condition, a single robust area of activation in the medial aspect of the left frontal superior gyrus (Brodmann areas 8, 9) remained.

Two aspects of the Goel et al. (1997) results were quite surprising. First was the absence of any right-hemisphere activation (even at a level of significance,  $p = .001$ , with no correction for multiple comparisons). Right-hemisphere activation of the prefrontal cortex (Brodmann area 47), the parietal cortex (Brodmann area 40), and the occipital cortex (Brodmann area 19) have been reported for spatial working memory tasks (Jonides, Smith, Koeppe, Awh, & Minoshima, 1993). Second, there was no parietal activation in either hemisphere (at a level of significance,  $p = .001$ , with no correction for multiple comparisons). The posterior parietal cortex (Brodmann area 40) is well documented to be involved in encoding an object's relative position with respect to other landmarks in the "where" pathway of the stream of vision (Mishkin & Appenzeller, 1990). If subjects were mapping the propositions onto spatial representations, one might expect neuronal activation of these regions. Indeed, Johnson-Laird (1994) predicts right hemisphere and parietal activation for the mental models theory.

It is possible that the absence of regions known to be involved in spatial processing was just a function of the fact that the deductive reasoning items used by Goel et al. (1997)—a combination of categorical syllogisms, implications, disjunctions, and conjunctions—do not all *overtly* involve spatial relations. Perhaps if the argument contents had explicitly required spatial encoding, they may have found right-hemisphere and parietal activation. We did not consider this a very strong possibility because both introspection and some cognitive theories suggest that syllogisms are mapped onto spatial representations by way of Venn diagrams or Euler circles. But given the surprising results of the first study, it seemed necessary to replicate the results for deductive reasoning and test this hypothesis.

To this end we carried out a [ $^{15}\text{O}$ ]  $\text{H}_2\text{O}$  PET study using three types of deductive argument forms: categorical syllogisms, three-term spatial relational items, and three-term nonspatial relational items. Examples of each are found in Table 1. We hypothesized that if any argument forms are to recruit the spatial encoding and spatial working memory centers, certainly the spatial relational items should. Moreover, categorical syllogisms are often said to be solved spatially (e.g., through the use of Venn diagrams and Euler circles), and nonspatial relational items may well be mapped onto spatial analogs (e.g., "heavier than" can be mapped onto "taller than"). Based on these considerations (and mental models theory), our expectation was that all of these argument

**Table 1.** Example Stimuli.

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Syllogism:
Some officers are generals.
No privates are generals.
Some officers are not privates.
Spatial relational:
Officers are standing next to generals.
Privates are standing behind generals.
Privates are standing behind officers.
Nonspatial relational:
Officers are heavier than generals.
Generals are heavier than privates.
Privates are lighter than officers.

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types should involve spatial encoding. Furthermore, we postulated that high-spatial subjects may be more prone to use spatial strategies than low-spatial subjects and selected subjects with a range of spatial abilities as determined by the WAIS-R Blocks Design subtest.

The purpose of this study was to (1) replicate the Goel et al. (1997) results regarding deductive reasoning with different deductive items and subjects and (2) to further explore the involvement (or noninvolvement) of spatial mechanisms in deductive reasoning.

We used a paradigm in which 12 normal subjects were presented with sets of three sentences on a computer screen and asked to make Yes/No judgments about the sentences while they underwent a brain scan using a [ $^{15}\text{O}$ ]  $\text{H}_2\text{O}$  PET technique. The stimuli were presented in four conditions. In the baseline condition, subjects made judgments about the semantic content of the sentences. The other three conditions required subjects to make judgments about whether the third sentence logically followed from first two sentences. Each reasoning condition contained either syllogisms, three-term spatial relational arguments, or three-term nonspatial relational arguments. The baseline condition contained all three of the argument types. Examples of the three types of arguments used appear in Table 1.

## RESULTS

Subjects' scores and times are noted in Table 2. There is a significant difference in scores across the three argument types ( $F(2, 10) = 3.7, p < 0.05$ ). Analytic comparisons using a paired  $t$  test show that the overall difference is due to the fact that subjects score higher on the nonspatial relational items than the spatial relational items ( $t(10) = 4.4, p < 0.05$ ). There are no significant differences in the time subjects took to respond to the

**Table 2.** Subjects' Mean Scores and Times.

	<i>Baseline</i>	<i>Syllogisms</i>	<i>Relational</i>	<i>Spatial</i>
Scores, % ( <i>SD</i> )		91 (6.0)	94 (2.0)	88 (5.0)
Time, ms ( <i>SD</i> )	5163 (1102)	7363 (820)	7436 (813)	7545 (749)
Number of items completed at bolus injection ( <i>SD</i> )	11.13 (2.2)	8.0 (1.2)	7.5 (1.3)	7.5 (1.1)
Number of items completed during scan ( <i>SD</i> )	11.4 (2.1)	7.9 (1.3)	8.0 (1.6)	6.8 (1.1)

different types of arguments. The overall scores are in line with published data (Evans et al., 1993).

We also divided the subjects into two groups based on their WAIS-R Blocks Design subtest scores and reanalyzed the behavioral data. One group received a mean score of 16.5 (*SD* = 2.2) on the Blocks Design, and the other received a mean score of 12 (*SD* = 1.1). There were no significant differences in the performance of the two groups in the deductive reasoning tasks.

The rCBF data are presented in Figure 1 and Table 3. The number of items subjects had completed at time of bolus injection and during the scan are reported in Table 2.

The syllogism condition (Syllogism – Baseline) resulted in activation of the left inferior frontal gyrus (Brodmann areas 45, 47), a portion of the left middle frontal gyrus (Brodmann area 46), the left middle temporal gyrus (Brodmann areas 21, 22), a region of the left superior temporal gyrus (Brodmann area 22), and a portion of the left cingulate gyrus (Brodmann areas 32, 24).

The spatial condition (Spatial – Baseline) resulted in activation of the inferior frontal gyrus (Brodmann area 45), a portion of the left middle frontal gyrus (Brodmann area 46), and a portion of the left cingulate gyrus (Brodmann areas 32, 24). The only nonfrontal areas activated were a region in the left middle occipital gyrus (Brodmann area 19) and a region of the lateral inferior temporal gyrus (Brodmann area 37).

The relational condition (Relational – Baseline) resulted in activation of the inferior frontal gyrus (Brodmann area 45), a portion of the left middle frontal gyrus (Brodmann area 46), and a portion of the left cingulate gyrus (Brodmann areas 32, 24). The only other region of significant activation was the left globus pallidus (lateral and medial).

We also directly compared the three reasoning conditions with each other. Neither the spatial relational minus nonspatial relational nor the nonspatial relational minus spatial relational conditions resulted in any regions of significant activation. The syllogism minus spatial relational condition resulted in activation of bilateral middle temporal gyri (Brodmann area 21), the left inferior frontal gyrus (Brodmann area 45), and the left superior frontal gyrus (Brodmann area 8). The syllogism minus nonspatial relational comparison activated the following left-hemisphere regions: middle temporal gyrus (Brodmann area 21), inferior frontal gyrus (Brodmann

area 45), superior frontal gyrus (Brodmann areas 8, 9), and middle frontal gyrus (Brodmann area 10). The subtraction of the syllogism condition from the nonspatial relational condition resulted in the activation of the left parieto-occipital sulcus (Brodmann area 7) and precuneous. The spatial relational minus syllogism comparison activated the right precuneous (Brodmann area 31).

Finally we divided subjects into high- and low-spatial groups based on their scores on the WAIS-R Block Design subtest and did a group by task comparison of the rCBF data. As with the behavioral data, there were no significant differences in the reasoning versus baseline activations between the two groups. In other words, testing explicitly for differential activations between the groups showed no regionally specific interactions.

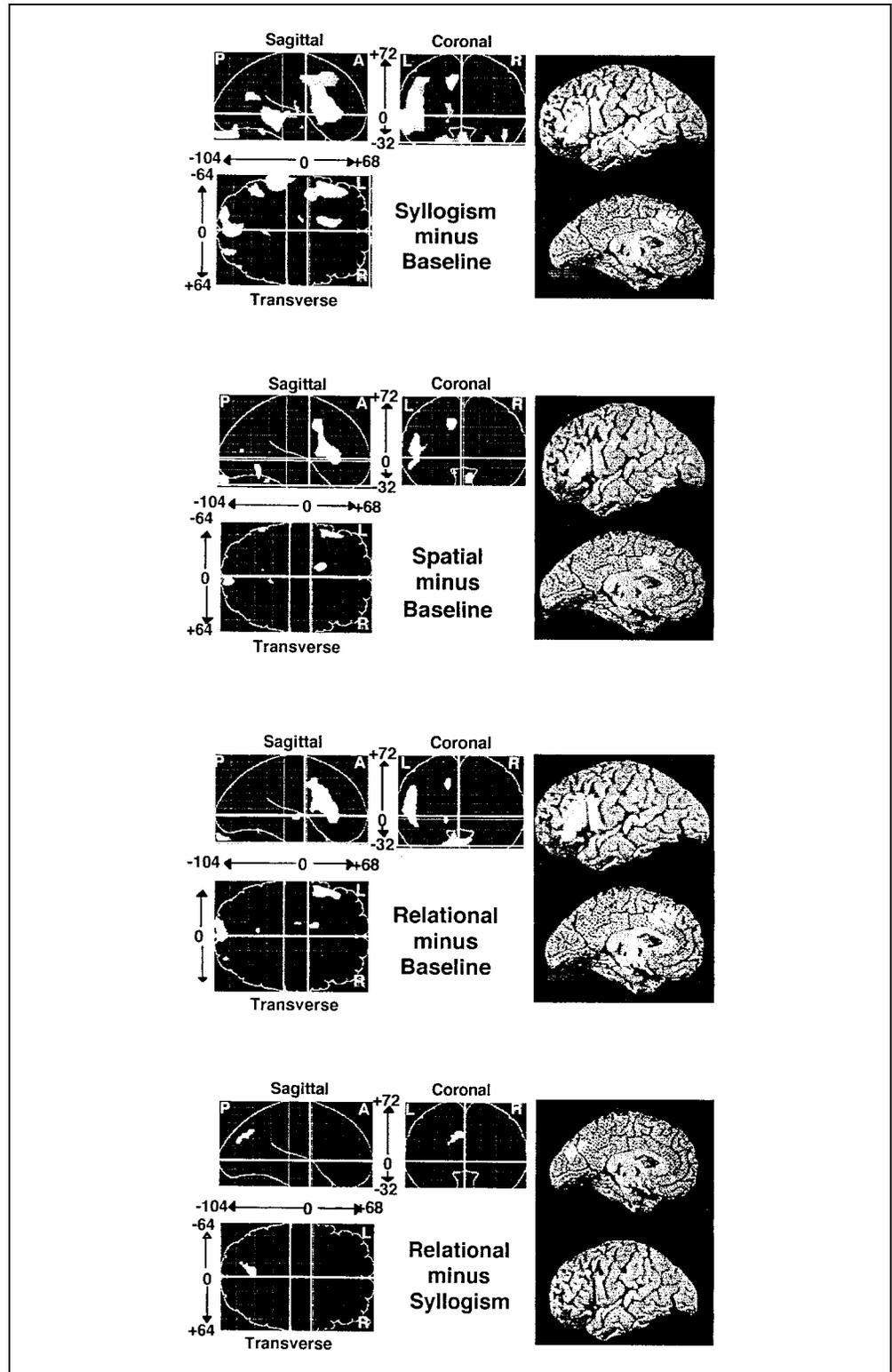
## DISCUSSION

The study was successful in replicating the deductive reasoning results of Goel et al. (1997), both with respect to the dominance of the left hemisphere and the involvement of the middle and inferior frontal gyri. The present results are also consistent with Goel et al. (1997) with respect to the absence of activation of the superior and medial left prefrontal cortex (Brodmann areas 8, 9) during the deductive reasoning task.

One difference between our present results and the previous results is that in the present study the areas of activation are larger, and the “hottest voxel” associated with an area has a higher *z* value than in the previous study. There are several plausible explanations for this. First, the argument forms in the current study were easier, leading to significantly better subject performance (66% correct in the previous study versus 91% correct in the current study). Second, in the first study, subjects alternated between conditions requiring inductive and deductive reasoning. In the present study, all conditions (except the baseline) required deductive reasoning. Third, the single deductive condition in the first study contained a heterogeneous mix of deductive argument forms. In the present study we used three distinct deductive conditions and each contained just one type of argument.

When the reasoning conditions are directly compared to each other, it turns out that the regions of activation in the two relational conditions (spatial and nonspatial) are identical. However, both relational conditions differ

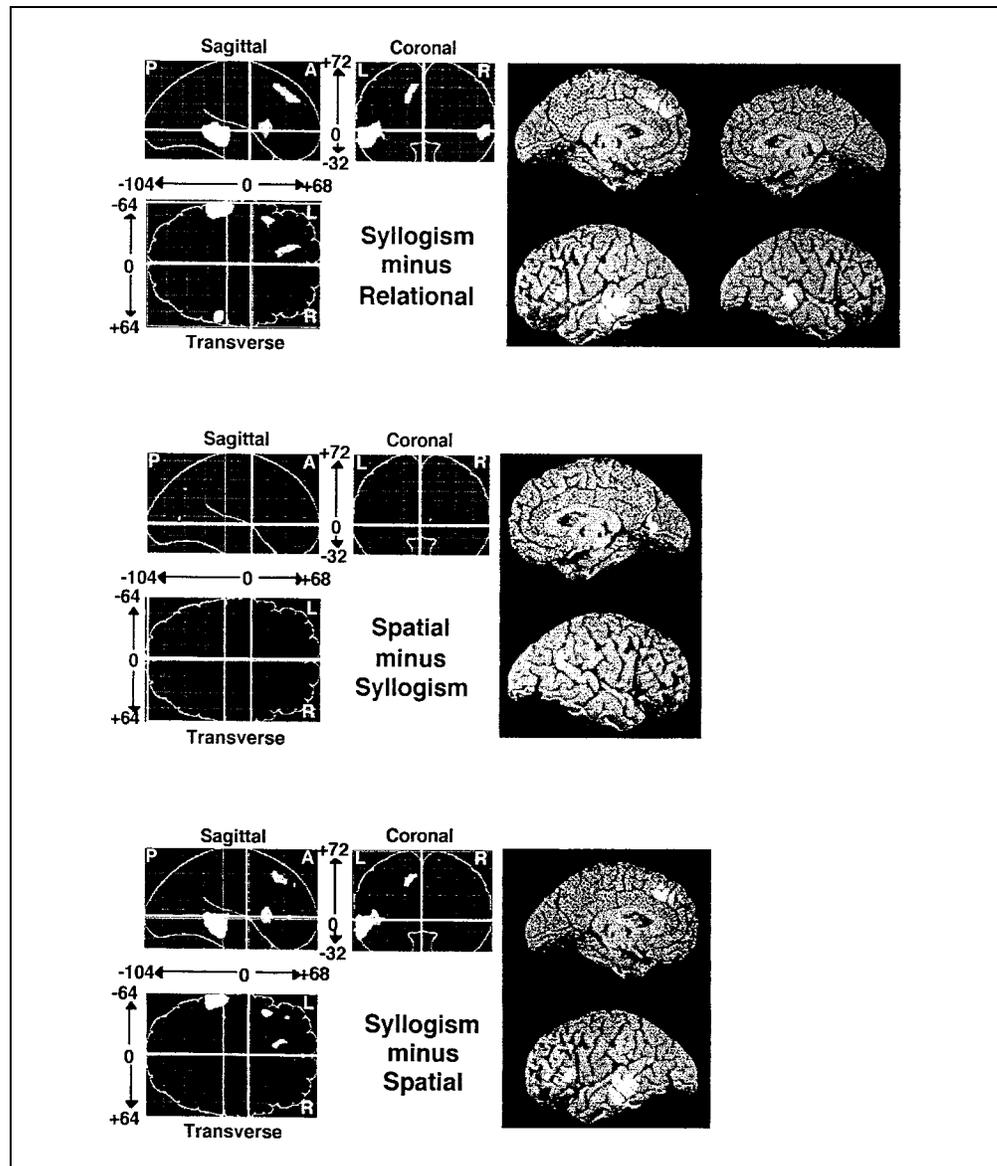
**Figure 1.** Location of significant increases in rCBF. Images are shown as standard SPM projections through sagittal, coronal, and transverse views of the brain (L = left, R = right, A = anterior, P = posterior). Areas of activation are also shown mapped onto the standard Talairach brain.



from the syllogism condition. The syllogism minus spatial relational condition leaves active regions of the left middle temporal gyrus (Brodmann area 21) and left inferior, middle, and superior frontal gyri (Brodmann areas 45, 10, 8, 9). The subtraction of the nonspatial relational condition from the syllogism condition gives similar results except that the temporal activation is bilateral. The pres-

ence of significant activation in the dorsolateral prefrontal cortex and the junction of the superior frontal and anterior cingulate gyri in the latter two subtractions suggests that the syllogism condition may require greater attentional and working memory resources. The prominent presence of the middle temporal lobe—a region associated with language and memory processes—may

Figure 1. Continued.



be indicative of a difference in strategy. For example, the syllogism task may place greater demands on the phonological loop of working memory.

The high- and low-spatial ability group comparison showed that the two groups activated identical cortical regions. This suggests that differing spatial ability did not result in (detectable) strategy differences during reasoning.

We are interpreting our results as indicating that human reasoning involves a distributed computational network in the left hemisphere spread out over the inferior dorsolateral and medial prefrontal cortex and temporal lobe. Given the complexity of our task, it is impossible at this stage to provide a detailed task analysis. However, it is reasonable to associate the activations of the dorsolateral frontal gyrus with working memory (Goldman-Rakic, 1994) and inferior frontal gyrus with language processes. The medial prefrontal cortex is considered to be instrumental in “executive attention” functions, per-

haps controlling working memory areas (Posner & Dehaene, 1994). The superior and middle temporal gyri are known to have language and memory-related functions. This gives us a picture of reasoning as language-based processing in working memory guided by a central executive mechanism.

There are of course other interpretations of the data. One reviewer suggested that these regions may have nothing to do with the reasoning process at all. The prominent involvement of Broca’s and peri-Broca’s areas in our study may be indicative of “intense internal conversations” that are used to encode the problems as a prerequisite to solution. These activations are so intense that they overwhelm any other activations that might actually correspond to the reasoning component.

This is a testable hypothesis that should be pursued in future studies. However, we think it an unlikely interpretation for three reasons. First, it is not the case that only Broca’s and peri-Broca’s areas dominate our results.

**Table 3.** Location and Characteristics of the Brain Regions that Remained Significantly Active After Each Subtraction.

<i>Location (Brodmann area)</i>	<i>Size (k)</i>	<i>Talairach coordinates</i>			<i>z score</i>	<i>%ΔCBF</i>
		<i>X</i>	<i>Y</i>	<i>Z</i>		
Syllogism – baseline						
Left inferior frontal gyrus (45, 47)	1119	–46	24	4	6.33	5.18
Left middle frontal gyrus (46)						
Left cingulate gyrus (24, 32)	317	–12	18	44	4.88	2.78
Left middle temporal gyrus (21, 22)	676	–52	–38	0	3.82	3.45
Left superior temporal gyrus (22)	161	–42	–54	20	4.11	2.54
Spatial relational – baseline						
Left inferior frontal gyrus (45)	303	–50	32	4	4.91	5.29
Left middle frontal gyrus (46)						
Left cingulate gyrus (24, 32)	106	–14	12	40	4.91	2.89
Left inferior temporal gyrus (37)	53	–52	–56	–8	3.76	2.79
Left middle occipital gyrus (19)	17	–40	–78	16	3.45	2.46
Right white matter	13	24	12	16	3.38	2.54
Nonspatial relational – baseline						
Left inferior frontal gyrus (45)	519	–50	24	12	4.99	4.33
Left middle frontal gyrus (46)						
Left cingulate gyrus (24, 32)	86	–12	8	40	4.21	2.64
Left globus pallidus (lateral and medial)	43	–14	–8	0	3.73	2.84
Nonspatial relational – spatial relational No active regions						
Spatial relational – nonspatial relational No active regions						
Syllogism – nonspatial relational						
Left middle temporal gyrus (21)	537	–52	–36	0	5.40	3.09
Right middle temporal gyrus (21)	143	52	–32	0	4.31	2.51
Left inferior frontal gyrus (45)	135	–44	16	4	4.25	2.55
Left superior frontal gyrus (8)	179	–16	36	32	3.99	4.27
Syllogism – spatial relational						
Left middle temporal gyrus (21)	489	–56	–32	0	5.30	3.14
Left inferior frontal gyrus (45)	113	–44	18	4	4.11	2.61
Left superior frontal gyrus (8)	112	–14	30	40	3.89	2.30
Left superior frontal gyrus (9)	12	4	44	36	3.53	2.20
Left middle frontal gyrus (10)	29	–38	38	0	3.40	2.60
Nonspatial relational – syllogism						
Left parieto-occipital sulcus (7)	132	–8	–68	36	3.93	2.83
Left precuneous						
Spatial relational – syllogism						
Right precuneous (31)	13	10	–64	20	3.45	1.71

There are three other regions involved (dorsolateral prefrontal cortex, superior medial frontal lobe, and temporal lobe). All of these regions remain significantly active even when we increase the confidence threshold to  $p = 0.0001$ . Second, this pattern of activation is very different from activation associated with passively viewing words, listening to words, or speaking words (Petersen, Fox, Posner, Mintun, & Raichle, 1988). It is, however, very similar to neuronal activity associated with a condition in which subjects viewed noun words and had to generate (infer) verbs (functions) associated with them (Petersen, et al., 1988). Third, studies involving inference with nonlinguistic stimuli have reported similar regions of activation, including robust activation of the inferior frontal lobe (Wharton et al., in review).

Although the cortical regions activated are of great interest, equally interesting is the absence of activation in certain regions, in particular the absence of right-hemisphere activation and the absence of any parietal activation, even in the explicitly spatial condition, which specifically demands (allocentric) spatial encoding.

The absence of right-hemisphere activation in our reasoning tasks is consistent with several findings in the literature. First, Gazzaniga and colleagues have administered simple reasoning tasks to split-brain patients and concluded that reasoning is a left-hemisphere phenomenon (Gazzaniga, 1985; Gazzaniga & Smylie, 1984). For example, they report that the left hemisphere will readily infer “boiling water” when presented with “water” and “pan” whereas the right hemisphere seems incapable of such inferences. Gazzaniga goes on to postulate a “left brain interpreter,” a mechanism that continuously elaborates and interprets information presented to it and readily draws inferences.

In a similar vein Deglin and Kinsbourne (1996) administered syllogisms to recovering schizophrenic patients before and after right- and left-hemisphere electroconvulsive therapy (ECT) suppression. They postulated a “left-hemisphere mechanism capable of decontextualized mental operations and a right-hemisphere mechanism that is context-bound and incapable of abstraction” to account for their results.

Second, there are a number of studies that have reported a disassociation between categorical and coordinate spatial encoding (Kosslyn, Koenig, Cave, Tang, & Gabrieli, 1989; Laeng, 1994). Coordinate encoding requires the representations of specific distance and location information. Categorical encoding is the relational representation of space as usually expressed in language by prepositions (e.g., on, under, beside, etc.). In the former instance, metric information is preserved. In the latter case, it is not. The encoding of categorical spatial relations, like those used in our argument forms, is lateralized in the left hemisphere, whereas the coordinate spatial encoding is lateralized in the right hemisphere (Kosslyn, et al., 1989; Laeng, 1994).

However, the lack of significant parietal activation is

more surprising. There are at least five possible explanations for it. (1) It is possible that spatial encoding was subtracted out in the semantic baseline condition (i.e., parietal cortex was already activated by merely reading about spatial relations). (2) Only spatial relations presented pictorially involve parietal lobe or right-hemisphere encoding. (3) Only egocentric representations are encoded in the parietal lobe. (4) Right-hemisphere and parietal involvement are subtle and diffuse and do not survive the statistical analysis at a significance level of  $p = .001$ . (5) The parietal cortex is not involved in language-based spatial reasoning. Spatial relations in linguistic reasoning bypass the parietal system and are encoded directly into the language system.

A recent [ $^{15}\text{O}$ ]  $\text{H}_2\text{O}$  PET study by Mellet et al. (1996) provides grounds for discounting the second and third possibilities. They had subjects construct 3-D cube assemblies from verbal instructions and report activation of a bilateral occipito-parietal-frontal network, including the superior occipital cortex, the inferior parietal cortex, and the premotor cortex. Furthermore, the spatial relations used by Mellet et al. (up, left, front, down, right, and back) were defined with respect to the first cube, not with respect to the subject. So the parietal lobe is involved in encoding linguistically presented allocentric spatial relations.

To test the fourth possibility—that our significance level of  $p = 0.001$  was too stringent to capture right-hemisphere and parietal involvement—we reanalyzed our data at a significance level of  $p = 0.05$ . This more liberal analysis did not change the results in any significant way. The sizes of the regions of activation of course increased, but the only other changes were that two regions that appeared as areas of activation in the syllogism condition at  $p = 0.001$ —right superior longitudinal fasciculus and the left superior temporal sulcus (Brodmann area 22)—appear as regions of activation in all three reasoning conditions. No parietal or right-hemisphere cortical activation was present even at level of  $p = 0.05$ .

This leaves open the first and fifth possibilities (i.e., that the parietal cortex was already activated by merely reading about spatial relations—and thus subtracted out—or that spatial relations in linguistic reasoning tasks bypass the parietal system and are encoded directly into the language system). We do not consider the first possibility very likely because only one-third of the items in the semantic condition involved overt spatial relations. A factorial design whereby each of the reasoning conditions had their own baseline would have allowed us to explicitly test this hypothesis. However, this design would have required 12 scans and we were restricted to 8 scans. We will adopt this factorial design in subsequent fMRI studies.

We currently favor the fifth hypothesis: that spatial relations in linguistic reasoning tasks bypass the parietal system and are encoded directly into the language system. It is, however, counterintuitive. Most of us have the

phenomenological experience of visualizing syllogisms as Euler circles or Venn diagrams or mapping spatial relational arguments onto a spatial matrix when solving these problems. It is possible that this experience is epiphenomenal and that the real work is being done by very different mechanisms. In any case, the present experiment design does not allow us to rigorously evaluate the fourth and fifth hypotheses. They will need to be addressed in a subsequent study.<sup>2</sup>

## CONCLUSION

We draw several conclusions from this study. First, as found by previous imaging studies (Goel et al., 1997) and patient studies (Deglin & Kinsbourne, 1996; Gazzaniga, 1985), logical reasoning—at least when administered linguistically—is predominately a language-based, left-hemisphere phenomenon. The prominent involvement of language areas and the failure of our study to find any activation of regions known to be involved in the encoding of spatial relations lends support to sentential models of reasoning and raises questions for spatially based models. Second, subjects seem to use strategies that rely on the same neuroanatomical substrate for relational argument forms, irrespective of whether they involve spatial or nonspatial relations. However, syllogisms seem to require strategies that call upon different neuroanatomical networks than do relational argument forms. Third, differing spatial abilities do not seem to result in any detectable strategy differences (insofar as these are encoded in differences in neuroanatomical substrate).

## METHOD

### Subjects

Twelve right-handed male university students with a mean age of 28.2 years ( $SD = 2.57$ ) and education level of 18.3 years ( $SD = 2.41$ ) were selected for participation on the basis of good performance on a pilot task. Subjects received a 30-min tutorial to ensure that they understood the notion of validity. Subjects were also required to complete the WAIS-R Blocks Design subtest. All subjects gave informed consent to participate in the study, and the experiment was approved by the York University Ethics Committee.

### Stimuli

The stimuli consisted of three types of deductive argument forms: syllogisms, three-term spatial relational arguments, and three-term nonspatial relational arguments, presented in three separate conditions. Examples of each type appear in Table 1. The nonspatial relational items included the following relations: colder than, hotter than, older than, younger than, newer than, softer than, darker

than, lighter than, warmer than, happier than, cheaper than, prettier than, healthier than, sicker than, slower than, louder than, faster than, stronger than, ruder than, smarter than, etc. The spatial relation items included the following relations: ahead of, behind, beside, in front of, above, next to, west, east, right of, left of, outside, inside, south, north, on top, under, etc. Fourteen different forms of syllogisms were used. They were all rated as having a 74% or greater correct response rate in the literature (Evans et al., 1993).

All the sentences were grammatical, meaningful, and of roughly equivalent length. There were 44 distinct arguments in each category. Half of the deductive items were valid and half were invalid. Subjects were required to make a decision about the sentences in each condition. The question specifying the decision was stated on the instruction screen that preceded the condition and applied to all trials in that condition. Subjects indicated responses by keypresses on a keyboard.

Stimuli presentation was subject-paced with the constraint that stimuli were continuously presented for a maximum of 12 sec, with an interstimulus interval of 750 msec. Subjects were instructed to move on to the next trial if the stimuli advanced before they could reply. Subjects' compliance with the study instructions were determined through error rate measurements and subject debriefing.

### Design

An experiment design involving four conditions, repeated once (for a total of eight), was used. All three argument forms were presented in the baseline condition, and subjects were required to process and comprehend the meaning of the sentences. Subjects were asked "how many of the three sentences on each screen have people as their subject?" The three argument forms were presented in three separate inference conditions. In these conditions subjects were asked whether the third sentence were *entailed* by the first two sentences. The sentences presented in the inference conditions were identical to those presented in the baseline condition. The ordering of conditions was counterbalanced across subjects. A subtraction technique was applied to statistically determine the independent contributions of brain regions to the processes in each condition.

### Data Collection and Analysis

Scanning was performed using the Scanditronix-II PC2048-15B camera with a 40-mCi injection of [<sup>15</sup>O] H<sub>2</sub>O and a 60-sec data acquisition time at a 12-min interval. The stimuli presentation began 60 sec prior to the injection and continued for at least 30 sec beyond the scan. PET data analysis were performed using statistical parametric mapping (SPM) software (MRC Cyclotron Unit, UK) in PROMATLAB (Mathworks, Natick, MA).

The data from each subject was first standardized for brain size and shape and reconstructed parallel to the intercommissural line (Friston et al., 1989, 1990; Talairach & Tournoux, 1988). Each image was smoothed to account for the variation in normal gyral anatomy using a Gaussian filter ( $\text{FWHM}_x \times \text{FWHM}_y \times \text{FWHM}_z = 20 \times 20 \times 15 \text{ mm}$ ). The effect of global differences in blood flow between scans was removed using an analysis of covariance (Friston et al., 1990). Comparisons between conditions were made by the  $t$  statistic using the adjusted pixel error variances for each condition estimated from the analysis of covariance. The  $t$  value for each pixel in each comparison was transformed to a normal standard distribution ( $z$  values) independent of the degree of freedom of the error. The resulting set of  $z$  values constitute an SPM (Friston, Frith, Liddle, & Frackowiak, 1991). All regions reported as being significantly activated exceed the  $p < 0.001$  level of significance, unless otherwise stated (Friston et al., 1991), and exceeded 10 voxels ( $\text{voxel} = 2 \times 2 \times 4 \text{ mm}$ ) in size.

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Reprint requests should be sent to Vinod Goel, Department of Psychology, York University, North York, Ontario, Canada M3J 1P3, or via email: vgoel@yorku.ca.

## Notes

1. A and B are valid deductive arguments while C and D are invalid arguments. However, C is plausible, while D is not.
2. As a more general point, given our results, we would want to recast subsequent studies so that we are not in a position of having to accept the null hypothesis.

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