Resolving Valid Multiple Model Inferences Activates a Left Hemisphere Network

Randall L. Waechter and Vinod Goel[1]

Department of Psychology, York University, Toronto, Ontario, Canada[2]

Abstract
Resolving multiple model syllogisms is more difficult than resolving single model syllogisms. Mental model theory predicts that visuospatial processing is critical for resolving syllogisms, and that demands on visuospatial processing systems will increase as reasoning problems become more difficult. An alternative account, the mixed-model approach, postulates that linguistic representations may augment visuospatial representations in multiple model problems. To test these competing hypotheses, we reorganized published archival fMRI data into single and multiple model problems, and reanalyzed it along this dimension. The critical comparison of multiple model versus single model problems revealed activation in both the left superior parietal spatial system and left frontal and temporal language areas, indicating that as reasoning problems become more difficult, reasoners augment any visuospatial model that they may have constructed with linguistic representations. This result is consistent with the mixed-model approach.

[1] V.G. is supported by a McDonnell-Pew Program in Cognitive Neuroscience Award, NSERC and CIHR grants, and a Premier's Research Excellence Award.
The authors would like to thank Dr. Oshin Vartanian for his invaluable insight and assistance with the writing of this manuscript.
[2] E-mail: vgoel@yorku.ca

1. Introduction

Reasoning is the cognitive activity of drawing inferences from given information. Arguments are considered valid only if the information contained in the premises provides absolute grounds for accepting the conclusion. One influential theory of logical reasoning, mental model theory, claims that determining the validity of logical arguments requires "the understanding of discourse (that) leads to a model of the relevant situation akin to one created by perceiving or imagining events instead of merely being told about them" (Johnson-Laird 1995, 999). Consider the following categorical syllogism:

A. All California snails are amphibians.
No amphibians can sing.
Therefore, no California snails can sing.

In the above example, individuals might mentally construct the following representation of the relationship between the premises and conclusion (Fig. 1): Mental model theory postulates that the reasoner determines whether

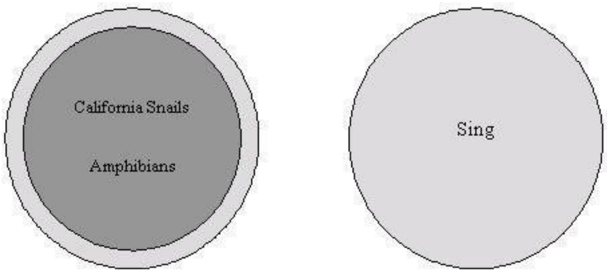


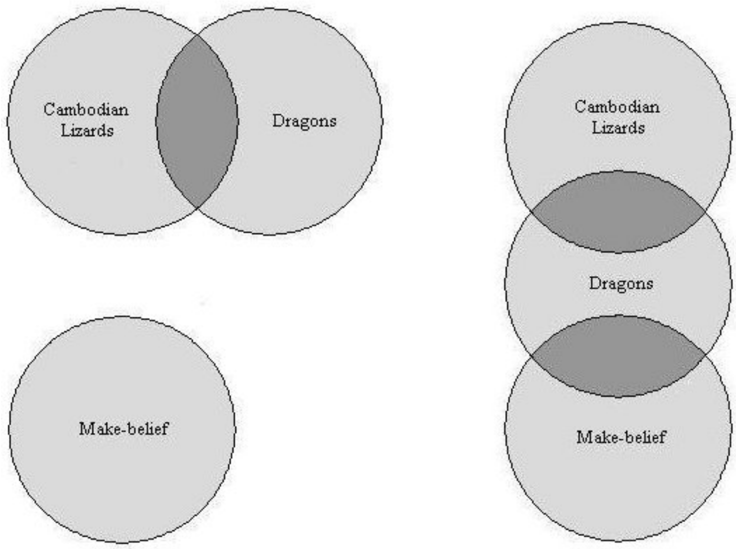
Fig. 1. Venn circle diagram of a single model syllogism.

the syllogism is valid or not by examination of such a spatially organized model. Specifically, the validity of the argument is tested by searching for alternative permutations of the first two premises that refute the conclusion. In the above example, the reasoner attempts to visualize the premises "All California Snails are amphibians" and "No amphibians can sing" in some other way than that pictured in Figure 1. In this case, the reasoner determines that the "California snails" and "Amphibians" circles *must completely* overlap to indicate that *all* of the California snails are amphibians, while the "Amphibians" and "Sing" circles *must be completely separate* to indicate that *no* amphibians can sing. As there is only one permutation of the premises in this example, and it is consistent with the conclusion, the argument must be valid. In fact, 90% of people given this particular syllogism draw the correct conclusion.

Now consider the following syllogism:

B. No Cambodian lizards are make-belief.
Some Cambodian lizards are dragons.
Therefore, some dragons are not make-belief.

Evaluation of this argument may result in the mental construction of a model like in Figure 2a. An important distinction can be made between



a. Reasoning Model Permutation # 1 b. Reasoning Model Permutation # 2

Fig. 2. Venn circle diagram of a valid multiple model syllogism.

syllogism A and B. The premises in syllogism A can only be arranged in one way, making it a 'single model' syllogism. The premises in the second argument can be arranged in more than one way, making it a 'multiple model' syllogism (Fig. 2). While the relationship between the components of the second syllogism differs across 2a and 2b, the original conclusion continues to hold in both cases.

Mental model theory predicts that resolving syllogism B will be more difficult as a result of the multiple ways in which the components of the syllogism can be represented. This increase in difficulty is measured by the percentage of participants who correctly classify the syllogism as valid or not and by an increase in the amount of time required to come to such a decision (Byrne & Johnson-Laird 1989). Indeed, only 55% of reasoners given this multiple model argument correctly classify it as valid. So what makes this syllogism, and multiple model syllogisms in general, so much harder to evaluate than single model syllogisms?

Past research provides two possible answers to the above question. The first answer relates to the number of spatial representations that the reasoner must analyze. Specifically, mental model theory postulates that multiple model problems are more difficult to resolve because the premises allow for the creation of alternative models that must be mentally constructed and considered before a conclusion regarding validity can be reached (Johnson-Laird 1995). This process takes time and loads on cognitive capacity, which leads to mistakes and inefficiencies in reasoning. Importantly, on this account, both single and multiple model problems are resolved using similar cognitive processes defined over visuospatial representations (Johnson-Laird 1995).

A second possible explanation is that different types of cognitive processes are engaged when resolving multiple and single model arguments. It has been hypothesized that linguistic, in addition to visuospatial processes, are activated when participants resolve more difficult (i.e., multiple model) reasoning items. Mani & Johnson-Laird (1982) consider this possibility based on data indicating that while subjects remember the gist of single model descriptions better, they have better memory for the verbatim details of multiple model descriptions. They explain these results by postulating the existence of two different types of encoding (i.e., representations): Propositional (i.e., linguistic) and analogical (i.e., visuospatial). According to this account, reasoning is a multi-step process. The first step consists of forming a loose and superficial linguistic/propositional representation of each sentence. This surface representation is sufficient for the encoding of verbatim information. The second step involves the construction of a visuospatial mental model that is consistent with the perceptual layout of the linguistic/propositional representation. Although linguistic/propositional representations are necessary for the formation of mental models, in all likelihood they are discarded after mental models are formed. The inference itself is defined strictly over the visuospatial model.

An alternative view for accommodating this data is to give the linguistic representations a more central role in the reasoning process, resulting in a "mixed model" account that involves a combination of linguistic and visuospatial processes (Van der Henst & Schaeken in press). When resolving single model problems, the reasoner may construct a spatial mental model of the relationship between the premises and conclusion. However, when the reasoning items become more complex (i.e., multiple model problems), the reasoner augments the mental construction and evaluation of spatial models with linguistic representations and inferential processes. According to this mixed visuospatial/linguistic approach, effects linked to a linguistic/propositional representation should occur more frequently with multiple model problems than with single model problems (Van der Henst & Schaeken in press).

Behavioural data has not been able to distinguish between these two explanations. An examination of brain activation while subjects solve single and multiple model problems provides another source of data to address the issue. If it is indeed the case that reasoning involves only the visuospatial system, then one would expect the involvement of the right hemisphere (Johnson-Laird 1995), or more accurately, occipital and parietal systems. Furthermore, it follows that as problems become more difficult (i.e., require the evaluation of multiple mental models), increasing task demands will result in greater activation in visuospatial systems.

However, if it is the case that linguistic representations play a significant role in the reasoning process, particularly in the case of multiple model problems, then one would expect greater involvement of left hemisphere frontal temporal systems in such trials. This prediction is consistent with much of the work in neuropsychology and cognitive psychology that stresses the importance and necessity of the left hemisphere for higher cognition including reasoning and problem solving. For example, tests of intelligence and general cognitive ability, such as the Scholastic Aptitude Test (SAT), Raven Matrices, and various vocabulary and reading comprehension tests, are highly correlated with logical reasoning (Stanovich & West 2000, Stanovich et al. 2004). These general cognitive tests are associated with activation in the left hemisphere, and specifically left lateral and dorso-lateral prefrontal cortex (Smith & Jonides 1997). Furthermore, it is reported that even after commissurotomy, where the two hemispheres are separated from each other, the left hemisphere continues to function at or close to preoperative levels (Gazzaniga 1970, 1989, 1995). The right hemisphere, on the other hand, is seriously impaired on cognitive tasks, especially in its ability to reason and solve problems (Gazzaniga 1970, 1989, 1995).

A series of neuroimaging and patient studies of human reasoning by various groups (Goel et al. 1998, Knauff et al. 2003, Langdon & Warrington 2000, Wharton et al. 2000) have consistently reported left hemisphere dominance for logical reasoning, while a series of studies by Goel and colleagues suggest that multiple neural pathways underlie human reasoning (Goel et al. 2000, Goel & Dolan 2001, 2003, 2004). According to Goel and colleagues, and consistent with a visuospatial account, a bilateral parietal (left $>$ right) system is activated when processing unfamiliar, nonconceptual or incoherent material (e.g., All P are B; All C are P; $\therefore$ All C are B), while (consistent with a linguistic account) a left frontal-temporal linguistic system is activated when processing familiar, conceptually coherent material (e.g., All dogs are pets; All poodles are dogs; ∴ All poodles are pets).

However, the neural basis underlying the resolution of single versus multiple model syllogisms has yet to be examined. To test competing hypotheses regarding the relative role of visuospatial and linguistic system involvement in reasoning, particularly in response to increasing number of mental models, we reorganized published archival data into single and multiple model problems, and reanalyzed it along this dimension.

2. Method

We conducted a reanalysis of data that was collected for an earlier reasoning study (Goel & Dolan 2003). The methods described here are those utilized in that study.

2.1. Subjects

We scanned 14 right-handed normal subjects using event-related fMRI, which indexes task-related activity, while the subjects 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 (UCL London) .

2.2. Stimuli

We reorganized the stimuli in the original study (Goel & Dolan 2003) to look at performance on valid single model (n=21) and multiple model (n=19) trials and 20 relevant baseline trials. The non-reasoning or baseline condition trials were generated by randomly taking approximately half of both the single and multiple syllogisms and switching around the third sentence such that the three sentences did not constitute arguments. All sentences used in the study were grammatical, meaningful, and matched for length across conditions. As such, we ended up with a 2 x 2 study design with difficulty (single versus multiple) and task (reasoning versus baseline) as the two variables of interest (see Fig. 3).

Stimuli from all conditions were presented randomly in an event-related design (Fig. 4). A "*" indicated the start of a trial at 0 s. The sentences

		Difficulty	
		Single Model	**Multiple Model**
Task	**Reasoning**	All California snails are amphibians. No amphibians can sing. No California snails can sing. (21)	No Cambodian lizards are make-belief. Some Cambodian lizards are dragons. Some dragons are not make-belief. (19)
	Baseline	All California snails are amphibians. No amphibians can sing. All marathon runners are healthy. (12)	No Cambodian lizards are make-belief. Some Cambodian lizards are dragons. Some parents are not respected. (8)

Total N (syllogisms) = 60

Numbers in brackets refer to the number of syllogisms in each cell

Fig. 3. Overall design of study with sample stimuli.

appeared on a 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). Participants responded by pressing a button on a keypad after the appearance of the last sentence.

In reasoning trials where the three sentences constituted an argument, participants had to determine the validity of the argument. In baseline trials, where the third sentence was unrelated to the first two, participants would begin to construct a representation of the problem, but could disengage and respond "no" with the appearance of the third unrelated sentence. Participants were instructed to respond as quickly as possible and move to the next trial if the stimuli advanced before they could respond. Participants reviewed example stimuli from each condition prior to being scanned to ensure that they understood the task. Participants 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 (1x1x1.5 mm voxels) and 48 T2*-weighted echoplanar images (64x64 3x3 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

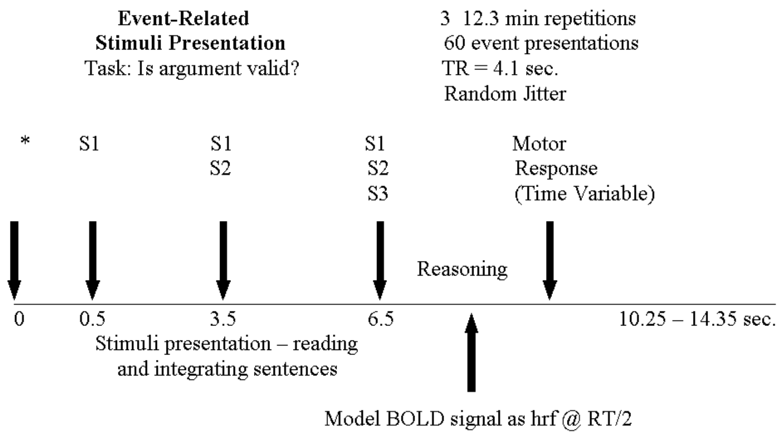


Fig. 4. Stimuli presentation.

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 $\pm$ 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 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

Imaging data were analyzed using Statistical Parametric Mapping (SPM 2) (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 co registered with the structural T1 volume and the structural volumes spatially normalized to the Montreal Neurological Institute brain template (Evans 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 128 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 statistical parametric map of the t-statistic for each voxel, which was subsequently transformed to a unit normal Z-distribution. The BOLD signal was modeled as a HRF at the midway point between the presentation of the third sentence and the motor response on a trial-by-trial basis. The presentations of all three sentences as well as the motor response were modeled out in the analysis. All results presented survived a significance level of p=.005 uncorrected.

3. Results

Overall behavioural results were analyzed in SPSS using repeated-measures ANOVA (single vs. multiple vs. baseline). This analysis revealed a significant difference in accuracy between the conditions, $F(2,12)=6.59$, $p=.01$. Further Bonferonni-corrected paired-samples t-test post-hoc analyses revealed a significant difference in accuracy between the single and baseline syllogisms, $t(1,13)=3.65$, $p<.01$ as well as the multiple and baseline syllogisms, $t(1,13)=3.42$, $p<.01$. There was no significant difference in accuracy or reaction time between the single and multiple model syllogisms.

Only those syllogisms that were answered correctly by participants were included in the imaging analysis. This step was taken to reduce variability in the imaging results as accurate responses indicate that participants were actually engaged in the reasoning task. The main effect of reasoning was determined by comparing all reasoning trials to all baseline trials [(single and multiple models) - baseline trials]. This analysis revealed activation in a largely left hemisphere system involving left lateral and dorso-lateral prefrontal cortex, left superior parietal lobule, left middle temporal lobe, primary visual cortex, precuneus, medial dorsal prefrontal cortex, and right lateral prefrontal cortex (Fig. 5).

To isolate brain regions associated with reasoning about multiple model syllogisms (but not single model syllogisms) and single model syllogisms (but not multiple model syllogisms), we directly compared the two conditions. A comparison of single model syllogisms versus multiple model

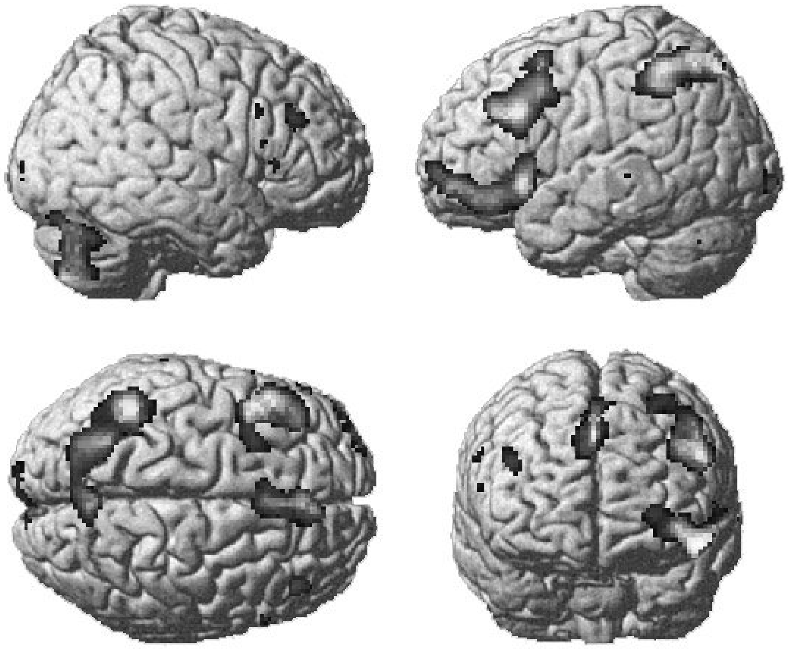


Fig. 5. Areas of activation for all reasoning items - baseline.

syllogisms (masked inclusively by the main effect of reasoning) revealed activation in a largely left hemisphere network consisting of medial dorsal prefrontal cortex (BA 8) (8, 38, 44; $z = 3.28$) and left superior parietal lobule (BA 7) (- 24, - 56, 40; $z = 3.59$) (Fig. 6).

The reverse comparison of multiple model syllogisms versus single model syllogisms, (masked inclusively by the main effect of reasoning) revealed activation in an exclusively left hemisphere network consisting of precuneus (BA 7) (-8, -76, 54; $z = 3.27$), inferior parietal lobule (BA 40) (- 38, - 70, 52; $z = 2.71$), superior temporal lobe (BA 21/22) (-66, -34, 4; $z = 3.45$), and lateral PFC (BA 47) (-50, 40, -14: $z = 2.99$) (Fig. 7).

4. Discussion

The behavioral results of the main effect of reasoning in the present study indicated that participants were engaged in the reasoning task and further analyses were warranted. The imaging results of the main effect of

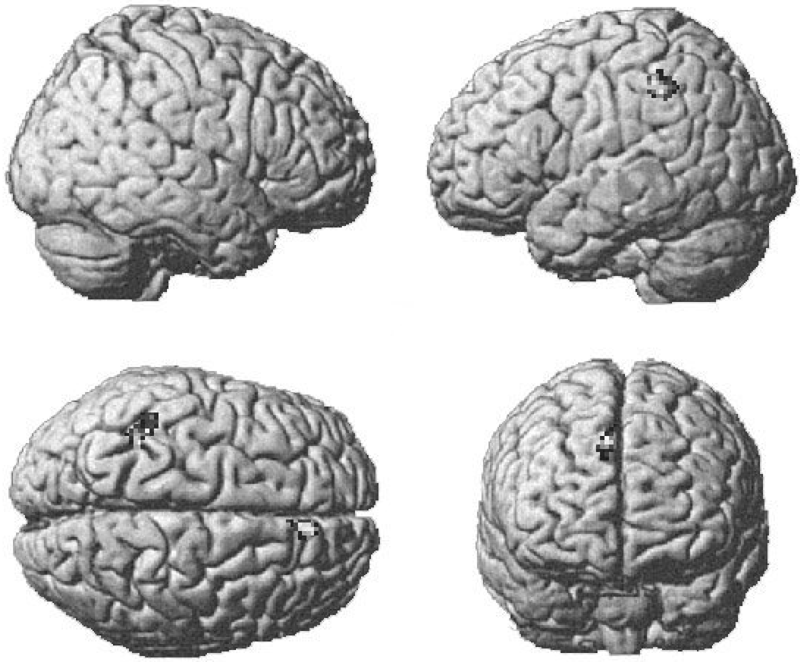


Fig. 6. Areas of activation for single model - multiple model.

reasoning replicated previous studies in which reasoning about items with familiar, conceptually coherent material activated a left frontal-temporal language-based "heuristic" system (Goel 2003, Goel et al. 2000, Goel & Dolan 2001, 2003, 2004, Knauff et al. 2003).

The single model versus multiple model comparison revealed activation in dorsal medial PFC as well as left superior parietal cortex. We did not observe significant right hemisphere activation for single model problems, but we did observe activation in visuospatial areas in the left hemisphere. These results are consistent with greater involvement of the visuospatial system in the resolution of single model syllogisms.

In contrast, the multiple model versus single model comparison revealed activation in both left superior parietal lobule and left frontal and temporal language areas. This activation of areas implicated in both linguistic and visuospatial processing is of particular interest. It supports the position that the difference between resolving multiple and single model problems is not one of just greater visuospatial and working memory resources but rather increased involvement of the language system. On the surface, this

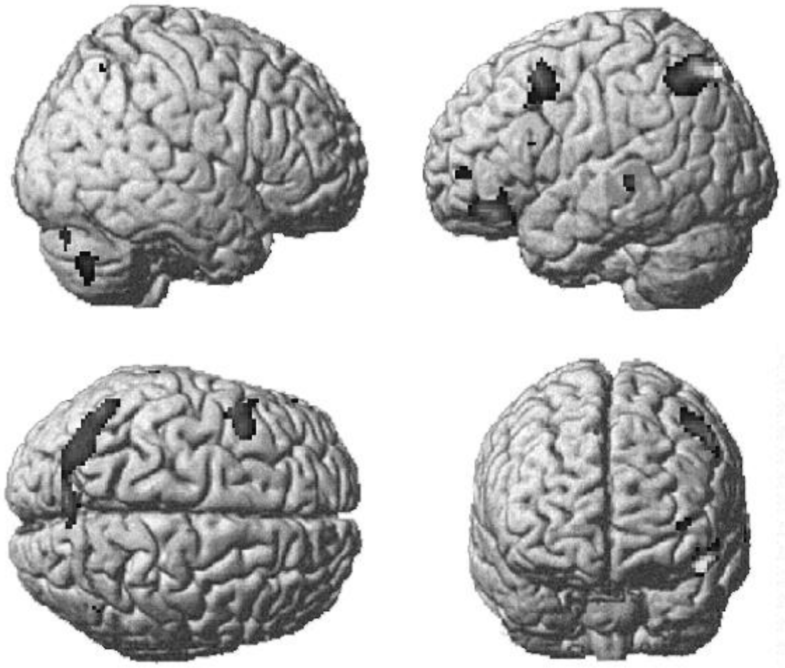


Fig. 7. Areas of activation for multiple model - single model.

result could be consistent with either the Mani & Johnson-Laird (1982) (i.e. superficial linguistic encoding which is not part of the inference process) or the Van der Henst & Schaeken (in press) (linguistic encodings play a critical role during inference) positions discussed above. However, the manner in which we have conducted our analysis supports the latter rather than the former account. Specifically, the BOLD signal in our study was modeled as a hemodynamic response function at the midway point between the presentation of the third premise and participant's motor response. The encoding of all three sentences and the participant's motor response were modeled as events of no interest. As such, if language-related areas are only involved in the first step of a multi-step model-building process, and are 'discarded' prior to the inference step (Mani & Johnson-Laird 1982), no language-related areas of activation should have been observed in our results. By contrast, if language-related areas are involved in the actual inference process (at least in reasoning about multiple model problems), as suggested by a mixed model approach (Van der Henst & Schaeken in press), language-related areas should be activated in our results. This is exactly what we found.

In summary, there is considerable evidence from both the lesion and neuroimaging literature that both visuospatial and linguistic processes play an important role in logical reasoning (Goel et al. 1998, Langdon & Warrington 2000, Wharton et al. 2000). What the current study adds to these data is that as reasoning problems become more difficult (i.e. move from single to multiple models) there is increased activation in left hemisphere linguistic systems, suggesting that reasoners are augmenting any visuospatial model that they may have constructed with linguistic representations, and that these representations play an important role in the inference process.

References

Ashburner, J. & Friston, K. J. (1999), 'Nonlinear spatial normalization using basis functions', *Human Brain Mapping* **7**(4), 254–266.

Byrne, R. M. J. & Johnson-Laird, P. M. (1989), 'Spatial reasoning', *Journal of Memory and Language* **28**, 564–575.

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, *in* 'Proceedings of the IEEE-Nuclear Science Symposium and Medical Imaging Conference', IEEE Press, Piscataway, NY, pp. 1813–1817.

Friston, K., Holmes, A., Worsley, K., Poline, J. B., Frith, C. & Frackowiak, R. (1995), 'Statistical parametric maps in functional imaging: A general approach', *Human Brain Mapping* **2**, 189–210.

Gazzaniga, M. S. (1970), *The bisected brain*, Appleton-Century-Crofts, New York, NY.

Gazzaniga, M. S. (1989), 'Organization of the human brain', *Science* **245**, 947–952.

Gazzaniga, M. S. (1995), 'Principles of human brain organization derived from split-brain studies', *Neuron* **14**, 217–228.

Goel, V. (2003), 'Evidence for dual neural pathways for syllogistic reasoning', *Psychologica* **32**, 301–309.

Goel, V., Buchel, C., Frith, C. & Dolan, R. J. (2000), 'Dissociation of mechanisms underlying syllogistic reasoning', *Neuroimage* **12**(5), 504–514.

Goel, V. & Dolan, R. J. (2001), '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.

Goel, V. & Dolan, R. J. (2004), 'Differential involvement of the left prefrontal cortex in inductive and deductive reasoning', *Cognition* **93**, B109–B121.

Goel, V., Gold, B., Kapur, S. & Houle, S. (1998), 'Neuroanatomical correlates of human reasoning', *Journal of Cognitive Neuroscience* **10**(3), 293–302.

Johnson-Laird, P. N. (1995), Mental models, deductive reasoning, and the brain, *in* M. S. Gazzaniga, ed., 'The Cognitive Neurosciences', MIT Press, Cambridge, MA, pp. 999–1008.

Knauff, M., Fangmeier, T., Ruff, C. C. & Johnson-Laird, P. N. (2003), 'Reasoning, models, and images: Behavioral measures and cortical activity', *Journal of Cognitive Neuroscience* **15**, 559–573.

Langdon, D. & Warrington, E. K. (2000), 'The role of the left hemisphere in verbal and spatial reasoning tasks', *Cortex* **36**(5), 691–702.

Mani, K. & Johnson-Laird, P. N. (1982), 'The mental representation of spatial descriptions', *Memory & Cognition* **10**(2), 181–187.

Smith, E. E. & Jonides, J. (1997), 'Working memory: A view from neuroimaging', *Cognitive Psychology* **33**(1), 5–42.

Stanovich, K. E., Sa, W. & West, R. F. (2004), Individual differences in thinking, reasoning, and decision-making, *in* J. P. Leighton & R. J. Sternberg, eds, 'The Nature of Reasoning', Cambridge University Press, Cambridge.

Stanovich, K. E. & West, R. F. (2000), 'Individual differences in reasoning: Implications for the rationality debate?', *Behavioural and Brain Sciences* **23**, 645–726.

Van der Henst, J. B. & Schaeken, W. (in press), 'The wording of conclusions in relational reasoning', *Cognition* (in press).

Wharton, C. M., Grafman, J., Flitman, S. S., Hansen, E. K., Brauner, J., Marks, A. & Honda, M. (2000), 'Toward neuroanatomical models of analogy: A positron emission tomography study of analogical mapping', *Cognitive Psychology* **40**(3), 173–197.

Worsley, K. J. & Friston, K. J. (1995), 'Analysis of fMRI time-series revisited — again', *NeuroImage* **2**, 173–181.

Index

brain imaging, 6
cognition, 3
cognitive neuroscience, 3
cortex
  dorsal medial prefrontal, 7
  dorso-lateral prefrontal, 3, 7
  parietal, 8
  prefrontal, 7
  temporal, 7
  visual, 7
fMRI, 4
language comprehension, 3
logical arguments, 0
memory
  working, 9
precuneus, 7
reasoning, 0, 2–4, 7, 10
  deductive, 4
representation
  propositional, 2
  spatial, 2
  visuospatial, 2
spatial mental models, 2
syllogism, 0