Evidence for Dual Neural Pathways for Syllogistic Reasoning

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Abstract

We review data from three neuroimaging studies of syllogistic reasoning that point to dual neural pathways for human reasoning. A frontal-temporal system processes familiar, conceptually coherent material while a parietal system processes unfamiliar, nonconceptual or incoherent material. We suggest that this is consistent with a dual mechanism account of reasoning consisting of heuristic and universal or formal processes. The frontal-temporal pathway corresponds to the “heuristic” system while the parietal pathway corresponds to the “universal” system. Reasoning about familiar situations automatically utilizes situation-specific heuristics, which are based on background knowledge and experience. Where no such heuristics are available (as in reasoning about unfamiliar situations), universal/formal methods must be used to solve the problem. In the case of syllogistic reasoning this involves a visuo-spatial system.

Logical Reasoning 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 which involves explicating information implicit in the premises. Valid deductive arguments involve the claim that the premises provide absolute grounds for accepting the conclusion.

Two theories of deductive reasoning (mental logic and mental models) dominate the cognitive literature. They differ with respect to the competence knowledge they draw upon, the mechanisms they invoke, the mental representations they postulate, and the neuroanatomical predictions they make. Mental logic theories (Braine, 1978; Henle, 1962; Rips, 1994) appeal to an underlying competence knowledge of proof theory (loosely speaking) and a mechanism of inference. This means that the subject has an underlying knowledge of the *inferential role* of the closed-form, or logical terms, of the language (e.g. 'all', 'some', 'none', 'and', etc,) and uses this knowledge to infer the conclusion. The claim here is that deductive reasoning is a rule governed syntactic process where internal representations preserve structural properties of linguistic strings in which the premises are stated. This linguistic hypothesis predicts that the neuroanatomical mechanisms of language (syntactic) processing underwrite human reasoning processes.

In contrast, mental model theories (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991) appeal to an underlying competence knowledge of model theory (loosely speaking) and a mechanism of searching through a state space.[1] This means that the subject has an underlying knowledge of the *meaning* of the closed-form, or logical terms, of the language (e.g. 'all', 'some', 'none', 'and', etc,) and uses this knowledge to construct and search alternative scenarios.[2] Furthermore, internal representations of the argument are said to preserve the structural properties of the world (e.g. spatial relations) that the sentences are about rather than the structural properties of the sentences themselves, as above. The claim is that deductive reasoning is a process requiring spatial manipulation and search. Mental model theory is often

[1] See Newell (1980) for a discussion of the relationship between search and inference.

[2] Whether there is any substantive difference between "knowing the inferental role" and "knowing the meaning" of the closed-form terms, and thus the two theories is a moot point, debated in the literature.

referred to as a spatial hypothesis and predicts that the neural structures for visuo-spatial processing contribute the basic representational building-blocks used for logical reasoning (Johnson-Laird, 1994).

There is, however, a third alternative provided by dual mechanism theories. At a very crude level, dual mechanism theories make a distinction between formal, deliberate, rule-based processes and implicit, unschooled, automatic processes, and predict the involvement of two different brain systems in human reasoning depending on which system is engaged. However, dual mechanism theories come in various flavours that differ on the exact nature and properties of these two systems. Theories differentially emphasize explicit and implicit processes (Evans & Over, 1996), conscious and preconscious processes (Stanovich & West, 2000), formal and heuristic processes (Newell & Simon, 1972), and associative and rule based processes (Goel, 1995; Sloman, 1996). The relationship among these proposals has yet to be clarified.

We have been carrying out a series of studies on the neural basis of logical reasoning to test these hypothesis. In Goel et al. (2000) we scanned 11 right-handed normal subjects using event-related fMRI, to measure task related neural activity, while they engaged in syllogistic reasoning. The study was designed to manipulate the presence of content in logical reasoning. Half of the arguments contained content sentences such as:

All dogs are pets

All poodles are dogs

 All poodles are pets

while the other half contained "no content" versions of these sentences such as:

All P are B

All C are P

 All C are B

The logically relevant information in both conditions was identical. Half of the arguments were valid, and the other half were invalid. For our baseline tasks we used trials in which the first two sentences were related but the third sentence was unrelated, as in the following examples:

All dogs are pets

All poodles are dogs

 All fish are scaly

and

All P are B

All C are P

 All N are D

Stimuli were presented one sentence at a time, with each sentence staying up until the end of the trial. Trials appeared randomly in an event-related design. The task in all trials was the same. Subjects were required to determine whether the conclusion followed logically from the premises (i.e. whether the argument was valid). In baseline trials, where the first two sentences were related, subjects would begin to construct a representation of the problem, but when the third, unrelated, sentence appeared they would immediately disengage the task and respond ‘no’. In reasoning condition trials, where the three sentences constituted an argument, subjects would continue with the reasoning component of the task after the presentation of the 3rd sentence. The difference between completing the reasoning task and disengaging after the presentation of the 3rd sentence isolates the reasoning components of interest. The data were modeled at the presentation of the 3rd sentence. The presentation of the first two sentences and subjects’ motor responses were modeled out. This basic design was used in each of the three studies discussed here.

If mental model theory is correct the reasoning trials should result in right hemisphere and parietal activation (Johnson-Laird, 1994). If mental logic theory is correct we would expect activation in left frontal and temporal lobe regions (language areas). Dual mechanism theory predicts engagement of two distinct (but unspecified) neural systems, depending on whether subjects respond in a "schooled", formal manner, or an intuitive, implicit manner. What we actually found was that the main effect of reasoning implicated large areas of the brain (Figure 1) including regions predicted by both mental model and mental logic theories.

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figure 1 approx here

However, closer examination revealed this to be a composite activation consisting of two dissociable neural systems. The content reasoning trials compared to no-content reasoning trials revealed activation in left middle / superior temporal lobe (BA 21/22), left temporal pole (BA 21/38), and left inferior frontal lobe (BA 47) (Figure 2). This is essentially a language and memory system. A similar network has been activated in previous studies of deductive reasoning using contentful sentences (Goel, Gold, Kapur, & Houle, 1997, 1998). The left lateralization of this system is consistent with the lesion data. For example, a study of temporal lobectomy patients on three term relational problems with semantic content (similar to above) reported that LH patient performance is more impaired than RH patient performance (Read, 1981). Similarly, studies with split-brain patients have concluded that (contentful) reasoning is a left hemisphere phenomenon (Gazzaniga, 1985; Gazzaniga & Smylie, 1984).

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figure 2 & 3 approx here

The reverse comparison of no-content reasoning trials vs. content reasoning trials resulted in activation of bilateral occipital (BA 19), bilateral superior and inferior parietal lobes (BA 7), and bilateral dorsal (BA 6) and inferior (BA 44) frontal lobes (Figure 3). This pattern of activation is known to be involved in the internal representation and manipulation of spatial information (Jonides, Smith, Koeppe, Awh, & Minoshima, 1993; Kosslyn, Koenig, Cave, Tang, & Gabrieli, 1989) and is very similar to that reported for certain types of mathematical reasoning involving approximation of numerical quantities (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999).

It is possible to argue that the patterns of activation revealed by the direct comparison of content and no-content conditions are just a function of the presence or absence of content words, rather than being indicative of different reasoning mechanisms. To exclude this possibility we examined the content by task interaction, controlling for the presence of content. The modulation of reasoning, by the addition of content [(content reasoning – content baseline) - (no-content reasoning – no-content baseline)] revealed activation in Wernicke's area. The reverse interaction, which examined the effect of the absence of semantic content, [(no-content reasoning – no-content baseline) - (content reasoning - content baseline)] activated left parietal cortex. This interaction analysis eliminates the above possibility and confirms the involvement of these two systems in the reasoning process.

Contrary to both, mental logic theories that predict the language (syntactic) system is necessary and sufficient for deductive reasoning, and mental model theories that predict the visuo-spatial system is necessary and sufficient for logical reasoning, Goel et al. (2000) found evidence for the engagement of both systems. The presence of semantic content engages the language and long-term memory systems in the reasoning process. The absence of semantic content engages the visuo-spatial system in the identical reasoning task. Before discussing the implications of these results for cognitive theories, let us consider some additional issues and data.

The Goel et al. (2000) study raises several interesting questions, one of which has to do with the involvement of a parietal visual-spatial system in the no-content or abstract syllogism condition. A second question has to do with the exact property of the stimuli that leads to the modulation of neural activity between frontal-temporal and parietal systems. Pursuing the first question lead to a clarification of the second question.

The first question is whether argument forms involving three-term spatial relations such as:

The apples are in the barrel

The barrel is in the barn

 The apples are in the barn

and

A are in B

B is in C

 A are in C

are sufficient to engage the parietal system irrespective of the presence of content? One rationale for thinking this might be the case is subjects' reported phenomenological experience of using a visuo-spatial strategy during these tasks. Secondly, neuroimaging studies have also shown the involvement of the parietal system in the encoding of relational spatial information (Laeng, 1994; Mellet et al., 1996). To address this question we carried out another fMRI study, this time using three-term relational arguments like the above (Goel & Dolan, 2001).

Goel and Dolan (2001) found that reasoning about abstract and concrete three-term relations, as in the above examples, recruited a bilateral parietal-occipital system, with greater involvement of parietal and occipital lobes in the abstract condition compared to the concrete condition. There was an absence of the two dissociable networks for concrete and abstract reasoning reported in the first study. In particular, the temporal lobe (BA 21/22) activation evident in concrete syllogistic reasoning in the first study, was conspicuously absent in the present study. This lack of temporal lobe (BA 21/22) activation in Goel and Dolan (2001) might be explained by analysing the nature of the content used in the two studies. The concrete sentences in Goel et al. (2000), were of the form "All apples are poisonous" whereas the concrete sentences in Goel & Dolan (2001) were of the form "John is to the right of Mary". The former sentence types predicate known properties to known objects. We have beliefs about whether they are true or false. By contrast, the latter sentence types do not allow for such beliefs.[3] This leaves open the interesting possibility that involvement of BA 21/22 in reasoning may be specific to content processing involving belief networks rather than just concrete contents.

This hypothesis was tested in Goel & Dolan (in press), where subjects were presented with arguments such as:

No reptiles are hairy

Some elephants are hairy

∴ No elephants are reptiles

containing sentences that subjects could be expected to have beliefs about, and belief-neutral arguments such as:

No codes are highly complex

Some quipu are highly complex

∴ No quipu are codes

containing sentences that subjects may not have beliefs about (because they may not know the meaning of one or more key terms). The referential terms in the two conditions were counterbalanced for abstract and concrete categories.

The results of this study replicated and clarified the results of Goel et al. (2000). Modulation of the reasoning task by absence of belief [(belief-neutral reasoning – belief-neutral baseline) - (belief-laden reasoning – belief-laden baseline)] revealed activation in the left superior parietal lobe (BA 7) unique to the belief-neutral condition. The reverse modulation [(belief-laden reasoning – belief-laden baseline) - (belief-neutral reasoning – belief-neutral baseline)] revealed activation of anterior left middle temporal gyrus (BA 21) activation unique to the belief-bias condition. These results confirm that a critical (sufficient) factor in the

[3] It is possible to generate relational sentences one can have beliefs about, for e.g. "London is north of Rome" or "Granite is harder than diamonds".

modulation of activity between these two neural systems is the presence of familiar or belief-laden content in the reasoning processes.

We now briefly address the question of how this dissociation maps onto the three cognitive theories of reasoning, with which we began our discussion. This is a complex question because the data do not fit neatly with any of the three theories. The two systems we have identified are roughly the language system and the visuo-spatial system, which is what mental logic theory and mental model theory respectively predict. However, each theory predicts that the system it postulates is sufficient for reasoning. Our data show it is not. A further complication is that mental logic theory implicates the syntactic component of language in logical reasoning. Our studies activate the semantic system and components of long-term memory.

Our results do seem compatible with some form of dual mechanism theory. However, as noted above, this theory comes in various flavours and some advocates may not be keen to accept our conclusions. The distinction that our results point to is between reasoning with familiar, conceptually coherent material vs. unfamiliar, nonconceptual or incoherent material, The former engages a left frontal-temporal system (language and long-term memory) while the latter engages a bilateral parietal (visuo-spatial) system. We believe that the frontal-temporal system is more "basic," and effortlessly engaged. It has temporal priority. By contrast, the parietal system is effortfully engaged when the frontal-temporal route is blocked due to a lack of familiar content, or when a conflict is detected between the logical response and belief-bias. This is very consistent with the dual mechanism account developed by Newell & Simon (1972) for the domain of problem solving. On this formulation our frontal-temporal system corresponds to the "heuristic" system while the parietal system corresponds to the "universal" system. Reasoning about familiar situations automatically utilizes situation-specific heuristics, which are based on background knowledge and experience. Where no such heuristics are available (as in reasoning about unfamiliar situations), universal (formal) methods must be used to solve the problem. In the case of syllogistic reasoning this may well involve a visuo-spatial system.

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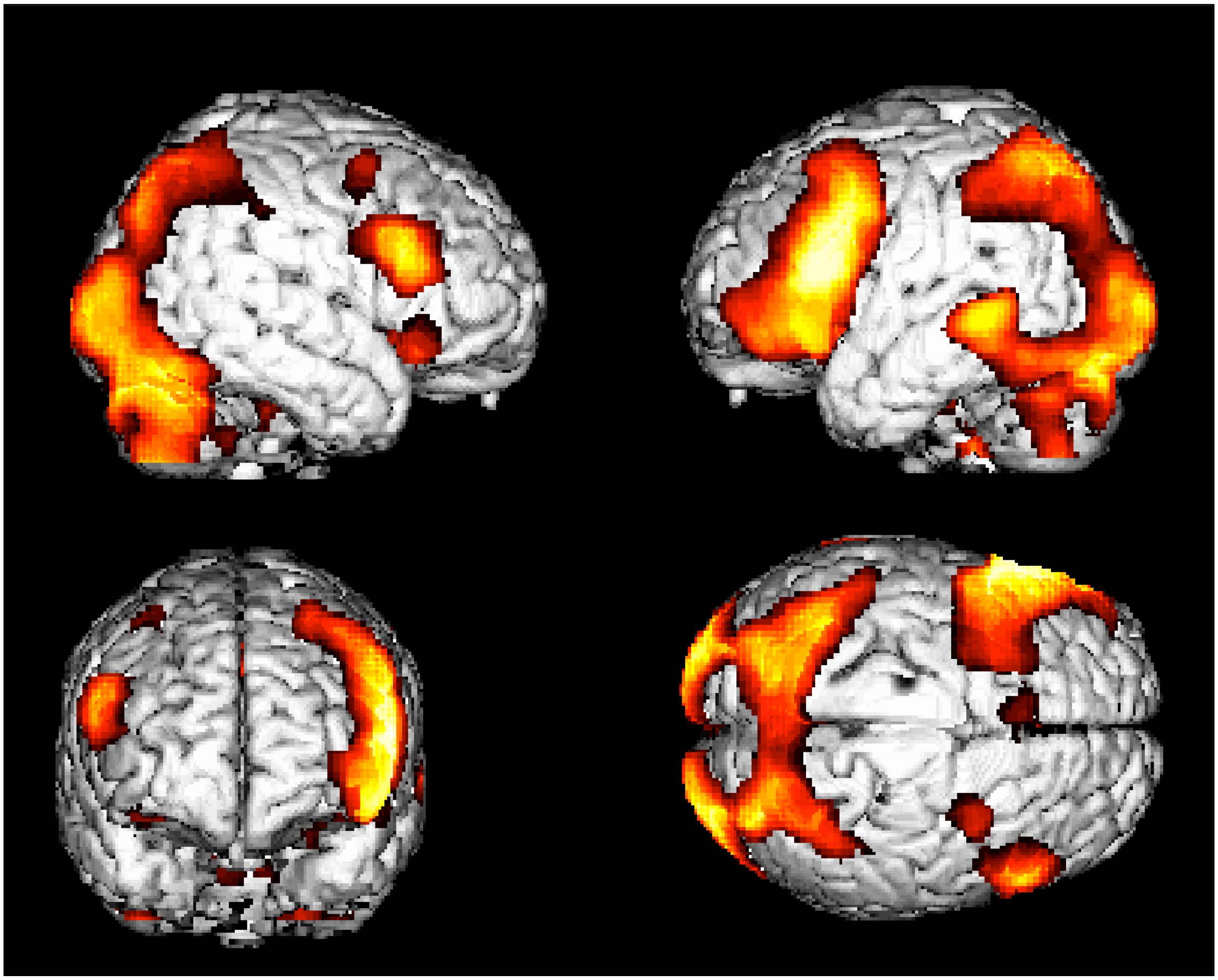
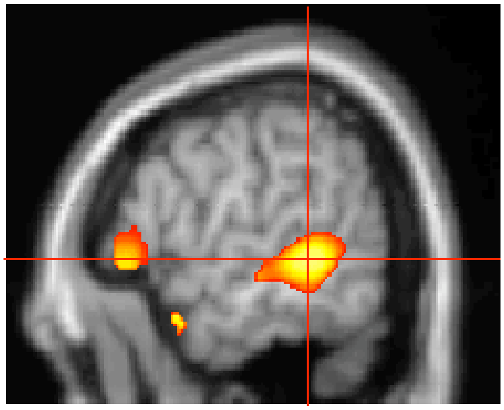
Figures

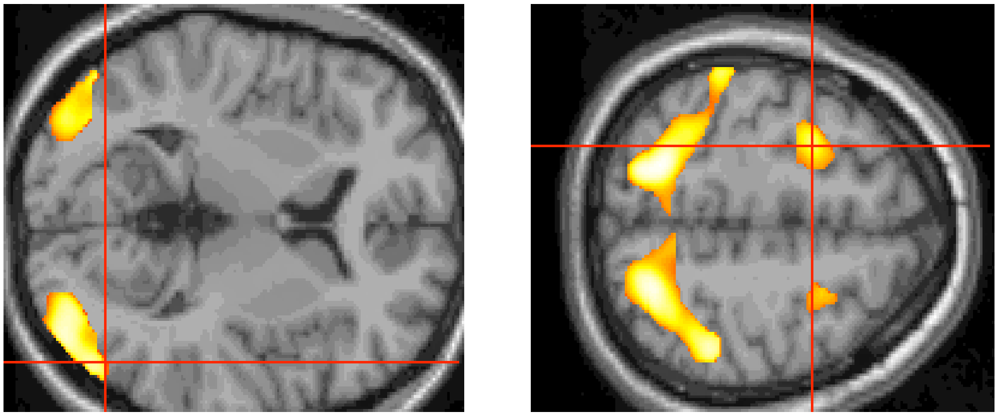
Figure 1. Main effect of reasoning [(content reasoning + no content reasoning) – (content preparation + no content preparation)] revealed activation of bilateral cerebellum (R > L), bilateral fusiform gyrus, left superior parietal lobe, left middle temporal gyrus, bilateral inferior frontal gyrus, bilateral basal ganglia nuclei (centered around the accumbens, caudate nucleus, and putamen), and brain stem.

Figure 2. The content reasoning - no-content reasoning comparison revealed activation of the left middle / superior temporal lobe (BA 21/22), the left inferior frontal lobe (BA 47), and bilateral (BA 17) and lingual gyri (BA 18).

Figure 3. The no-content reasoning - content reasoning comparison revealed activation of (a) bilateral occipital (BA 18, 19) and (b) bilateral superior and inferior parietal lobes (BA 7, 40), bilateral precentral gyrus (BA 6), and bilateral middle frontal gyrus (BA 6).







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