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The seats of reason? An imaging study of deductive and inductive reasoning

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We carried out a neuroimaging study to test the neurophysiological predictions made by different cognitive models of reasoning. Ten normal volunteers performed deductive and inductive reasoning tasks while their regional cerebral blood flow pattern was recorded using [^{15}O]H_2O PET imaging. In the control condition subjects semantically comprehended sets of three sentences. In the deductive reasoning condition subjects determined whether the third sentence was entailed by the first two sentences. In the inductive reasoning condition subjects reported whether the third sentence was plausible given the first two sentences. The deduction condition resulted in activation of the left inferior frontal gyrus (Brodmann areas 45, 47). 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). Induction was distinguished from deduction by the involvement of the medial aspect of the left superior frontal gyrus (Brodmann areas 8, 9). These results are consistent with cognitive models of reasoning that postulate different mechanisms for inductive and deductive reasoning and view deduction as a formal rule-based process.

Key words: Cognition; Deduction; Frontal lobes; Induction; Inference; Positron emission tomography; Reasoning

Introduction

Reasoning in the activity of evaluating arguments. All arguments involve the claim that one or more propositions (the premise) provide some grounds for accepting another proposition (the conclusion). Philosophers have sorted arguments into two broad categories – induction and deduction – based on the nature of the relationship between premise and conclusion. Valid deductive arguments involve the claim that their premises provide absolute grounds for accepting the conclusion. For example: (A) All men are mortal; Socrates is a man; therefore, Socrates is mortal. Validity is a function of the logical structure as opposed to sentence content. Arguments where the premises provide only limited grounds for accepting the conclusion are broadly called inductive arguments. For example: (B) Socrates is a cat; Socrates has 32 teeth; therefore, all cats have 32 teeth. (C) Socrates is a cat; Socrates has a broken tooth; therefore, all cats have a broken tooth.

Neither is a valid argument. However, most of us would be prepared to accept the conclusion in (B) as plausible or reasonable but we would not accept the conclusion of (C) as plausible or reasonable. Interestingly, both arguments have an identical logical structure; they differ only in content. So, unlike deduction (e.g. A), induction (e.g. B, C) is a function of the content of the sentence and our knowledge of the world. It is usually a matter of knowing which properties generalize in the required manner and which do not.

While philosophers are interested primarily in the epistemic relationship between premises and conclusion, psychologists are concerned with the cognitive processes/mechanisms involved in drawing the inference. Cognitive theories of reasoning can be divided into two broad categories. There is a class of theories that differentiate between inductive and deductive reasoning and postulate different mechanisms to explain each[1,2] and another class of theories that do not differentiate between induction and deduction and postulate a unitary account of human reasoning.[3,4]

The class of cognitive theories that differentiate between deduction and induction accept the philosophers' formulation of deduction as a formal rule governed process. They claim that the human organism in endowed with a competence knowledge of deduction in the form of internalized rules similar to those of formal logic.[1,2] When subjects successfully draw valid inferences, they are displaying their underlying competence. When they make errors, these errors are explained in terms of performance factors such as memory limitations, attentional factors, failure to engage the task, etc.

Cognitive models of induction take a very different form. Induction is typically viewed as a form of hypothesis generation and testing, where the crucial issue is one of searching a large data base and determining which pieces of information are relevant and how they are to be mapped on to the present situation.[5,6] The determination of relevance and generalization is thought to require enormous amounts of world knowledge and experience but no mechanisms adequate for the task have been discovered.

This class of theories postulates causally distinct cognitive/computational processes/mechanisms for inductive and deductive reasoning. Standard assumptions are used to interpret PET localization data: (i) distinct cognitive functions are associated with distinct neurophysiological operations, (ii) distinct operations are unaffected by preceding or following operations, (iii) complex operations are no more than the sum of their parts, (iv) each operation has a fixed spatial location, (v) subjects can be made to apply the same operation to a given task, (vi) spatial contiguity and temporal simultaneity correspond to causal connectedness, and (vii) there is a direct mapping between computational functions and the neurophysiological substrate. These theories predict that distinct neurophysiological structures will underlie inductive and deductive reasoning. Furthermore, deductive reasoning, being a formal, rule-governed process defined over the structure of language, will activate the left hemisphere more than the right hemisphere and will implicate some of the same structures involved in language processing.

The second class of theories offers a unitary account of human reasoning. Two such accounts are the mental models theory[4] and the content-specific schemas theory.[3] On the mental models account,[4,7,8] we have not internalized the rules of formal logic. Rather, we have knowledge that allows us to semantically comprehend an argument and construct non-linguistic mental models that are structurally isomorphic to the situation described in the premises of the argument. The process of inference is one of searching a state space for alternative models. If we can construct no models in which the premises are true but the conclusion is not, then the argument is valid. If the conclusion holds in most models of the premises, it is probable. If the conclusion holds in only one model of the premises, it is possible. If there are no models of the premises in which the conclusion holds, the argument is invalid. Successful model construction and search of the state space largely mirrors the application of the rules of logic. Induction differs from deduction only in the construction of the model, the former requiring the addition of information not found in the premises.

Another unitary model is offered by the schemas theory.[3] Again, this theory does not postulate any specific knowledge of deduction, but instead relies on general-purpose reasoning knowledge extracted from content-specific schemas or scripts for both deductive and inductive reasoning. Unitary models do not call for a clear cognitive/computational distinction between induction and deduction. Furthermore, because mental models are nonlinguistic and often spatial, Johnson-Laird[8] has predicted that the right (rather than the left) hemisphere will have a prominent role in deductive reasoning.[8]

The purpose of this study is to identify the neurophysiological substrates associated with inductive and deductive reasoning and to bring this data to bear on the evaluation of the different cognitive models of human reasoning. The results will also be relevant in revealing the extent of the involvement of the prefrontal cortex in the two types of reasoning.

Subjects and Methods

Subjects: Ten right-handed male university students (mean age 28.4 years, s.d. 4.03), with an education level of 18.4 years (s.d. 4.21) were selected for participation from a set of 25 students on the basis of good performance on a pilot task. Each subject received a brief tutorial to ensure that they understood the notion of validity and the distinction between deduction and induction. The 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 92 argument forms of the type presented above in examples A–C and in the Appendix. All the sentences were grammatical, meaningful and of roughly equivalent length. Half of the items fell in the deductive category and half in the inductive category. In the deduction condition, half of the items were syllogisms and the other half were implications, disjunctions, and conjunctions. Half of the deductive items were valid and half of the inductive items were plausible. 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 key presses on a keyboard.

Stimuli presentation was subject-paced with the constraint that stimuli were continuously presented for a maximum of 10 s, with an interstimulus interval of 750 ms. Subjects were instructed to move on to the next trial if the stimuli advanced before they could reply. The sequential ordering of conditions was counterbalanced across subjects. Subjects' compliance with the study instructions was determined through error rate measurements and subject debriefing.

Design: An experiment design involving three conditions, repeated once (for a total of six) was used. The baseline condition required the subject 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?' In the deductive inference condition subjects were asked whether the third sentence was entailed by the first two sentences. In the inductive inference condition subjects were asked whether the third sentence was plausible given the first two sentences. The sentences presented in the deductive and inductive conditions were identical to those presented in the baseline condition. A subtraction technique was applied to statistically determine the independent contribution of brain regions to the process in each condition.

Data collection and analysis: Scanning was performed using the Scanditronix-II PC2048-15B camera with a 40 mCi injection of $[^{15}O]H_2O$ and a 60 s data acquisition time at a 12 min interval. Stimulus presentation began 30 s prior to the injection and continued for 30 s beyond the scan. PET data analysis were performed using statistical parametric mapping software (MRC Cyclotron Unit, UK) in PROMATLAB (Mathworks, Natic, MA). The data from each subject were first standardized for brain size and shape and reconstructed parallel to the intercommissural line.[9–11] Each image was smoothed to account for the variation in normal gyral anatomy using a Gaussian filter (FWHMx × FWHMy × FWHMz = 20 × 20 × 15 mm). The effect of global differences in blood flow between scans were removed using an analysis of covariance.[9] Comparisons between conditions were made to 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 a statistical parametric map.[12] All regions reported as being significantly activated exceed the $p < 0.001$ level of significance.[12]

Results

Subjects' response times increased from the baseline condition (3640 ms) to the deduction (5870 ms) and induction (5505 ms) conditions as expected. The deduction response times were significantly higher than the induction response times ($t(9) = 2.5$, $p = 0.03$). Performance was 85% correct for baseline, 67% correct for deduction, and 75% correct for induction. These results are in line with published data.[13]

The data are presented in Fig. 1 and Table 1. The deduction condition (Fig. 1, deduction–baseline) 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 (Fig. 1, induction–baseline) 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 non-frontal 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).

The differences in the activation in the two reasoning conditions can be seen directly by subtracting the images of the deduction condition from the images of the induction condition (Fig. 1, induction–deduction). What remains is a single robust area of activation in the medial aspect of the left frontal superior gyrus (Brodmann areas 8, 9). The involvement of this region

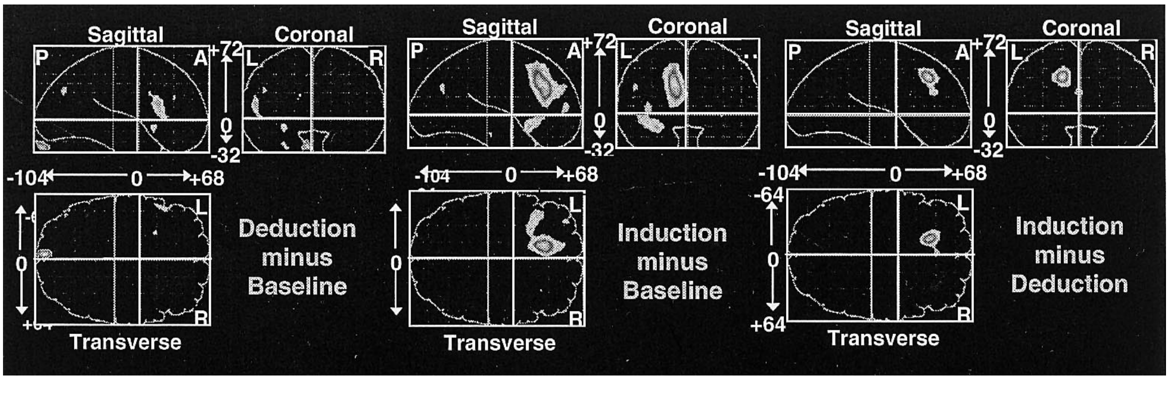

FIG. 1. Location of significant increases in regional cerebral blood flow. Images are shown as standard statistical parametric map projections through sagittal, coronal, and transverse views of the brain. L, left; R, right; A, anterior; P, posterior.

Table 1: Location and characteristics of the brain regions that remained significantly active after each subtraction

Location (Brodmann area)	Size (k)	Talairach coordinates			z score	%△CBF
		x	y	z		
Deduction–baseline						
L inferior frontal gyrus (45)	120	–52	18	16	3.81	3.65
L inferior frontal gurus (47)	28	–26	16	–4	3.71	1.99
L superior occipital gyrus (19)	23	–42	–74	28	3.54	2.83
Induction–baseline						
L cingulate gyrus (24,32) L medial frontal gyrus (9) L superior frontal gyrus (8,9)	934	–12	28	28	5.47	3.38
L inferior frontal gyrus (47)	221	–28	18	–12	4.63	2.92
L middle frontal gyrus (10)	44	–36	52	8	3.88	4.30
L superior occipital gyrus (19)	28	–46	–70	28	3.41	3.07
L inferior temporal gyrus (20)	12	–56	–18	–20	3.43	3.35
R white matter	15	30	28	0	3.52	2.55
Induction–deduction						
L superior frontal gyrus (8)	320	–16	32	36	5.06	2.67
L superior frontal gyrus (9)	7	–12	54	24	3.28	2.41

CBF, cerebral blood flow; L, left; R, right

of the frontal cortex in induction cannot be attributed to increased complexity of the task. By every measure (reaction times, performance scores, and subject feedback) deduction was the more complex task.

Discussion

Our results indicate that deductive and inductive reasoning tasks differentially involve the left prefrontal cortex. Given the many caveats that apply to the interpretation of localization studies (noted above), our results affirm the philosophical distinctions between deductive and inductive reasoning and support the category of cognitive models that maintain this distinction. Furthermore, the confinement of the activation associated with the deductive task to the left hemisphere, its proximity to Brocah's area, and the absence of activation in the parietal spatial regions are all contrary of the predictions made by the mental models theory[8] and suggest that deduction may be primarily a linguistic, rule-governed activity rather than a process of constructing and searching mental models. However, this interpretation is highly speculative at this point. First, our items were primarily non-spatial, linguistic items. Explicitly spatial relational items or reasoning tasks presented pictorially may give very different results. Second, our subjects were highly educated, preselected for good performance and briefed on the topic. This undoubtedly gives us a cleaner signal, and hence a sharper distinction, than may be obtained in naive subjects.

The left dorsolateral prefrontal cortex has been associated with semantic memory retrieval and episodic memory encoding in several PET studies[14–16] and has been linked with working memory by Goldman-Rakic.[17] Is it possible that the activation we are picking up in the deductive reasoning condition is just one of these memory functions? We can eliminate episodic memory encoding as a possible cause of the activation because it would also be present in the baseline condition and should subtract out. That the activation in part is due to semantic memory retrieval seems more plausible. The formal rules theory requires the retrieval of the rules, and mental model theory and the schema theory require access to semantic and world knowledge. But interestingly, on all accounts, the induction condition would also require access to the same semantic and world knowledge. Activation of this lateral region did not occur in the induction condition. One way of understanding this result is that the formal rules theory is on the right track and that this region of the prefrontal cortex is used to retrieve formal, rule-based knowledge while the retrieval of open-ended world knowledge involves more medial prefrontal structures. This particular interpretation would be consistent with the several studies that have activated the left dorsolateral prefrontal cortex with rule-governed tasks such as the Wisconsin Card Sort.[18]

The working memory interpretation of the activation associated with the deduction condition also has some merit. Feedback from our subjects confirms that the deduction condition places a much higher demand on working memory than induction. We are currently investigating working memory demands of inductive and deductive reasoning in a behavioural study and will attempt to factor it out in a subsequent imaging study.

There is a historical association of the left prefrontal cortex with the cognitive processes of generalization and abstraction. More recently this region has been linked to the storage of large-scale knowledge structures or scripts.[19,20] Both the access to a large quantity of knowledge and the mechanisms that allow for relevant generalization and abstraction are essential for induction. We take our results to mean that this mechanism requires a distributed computational network prominently involving the left medial prefrontal cortex.

At least two other PET studies have elicited activation of the same left medial frontal lobe area in a reasoning task involving a 'theory of mind' condition.[21,22] Authors of both studies associated the activation of the left medial prefrontal cortex to the requirements of 'theory of mind' reasoning involving mental state terms. In light of the present study it may be more parsimonious to associate the activation with reasoning involving generalization and abstraction over world knowledge rather than mental state terms.

Equally interesting, a study involving reasoning in chess did not find any significant activation of the left medial prefrontal cortex.[23] The only left frontal activation reported was restricted to the orbito-frontal cortex, a region also activated in both of our reasoning conditions. Again, given the formal, rule-governed nature of chess, which means it has much more in common with deduction than induction: this is consistent with our findings. It is worth noting that two of these three studies used pictorial stimuli, suggesting that our results are independent of our linguistic stimuli.

These findings also speak to a number of existent results in the cognitive neuroscience literature. One of the most puzzling findings is that patients with frontal lobe lesions often do reasonably well on laboratory IQ tests but experience significant difficulty in coping with real world problems and situations.[24,25] It may be possible to reconceptualize this puzzle in terms of induction and deduction. IQ tests often include a number of deductive reasoning items. They also include inductive items, but these tend to be informationally improvised, involving artificial closed worlds. Coping in the real world mainly requires inductive reasoning in an information-rich open-ended environment. A speculative generalization would lead us to expect that patients with focal lesions in the left medial prefrontal cortex may perform relatively well on IQ tests yet be impaired in their ability to function in the world at large.

Conclusion

We suggest that (i) the classical distinction between deduction and induction has a neurophysiological basis, contrary to the predictions made by the unitary cognitive models of reasoning; (ii) deduction (in the form we administered it) results in activations of neuronal regions associated with language (syntactic) processing rather than spatial modelling, which is consistent with the formal rules theory but not necessarily the mental models; (iii) the medial region of the left prefrontal cortex seems to be necessary for inference tasks involving generalization and abstraction over world knowledge; (iv) induction and deduction may provide useful categories for further probing frontal lobe function.

So as not to overstate our case, we remind the reader of the fragility of some of the assumptions (noted above) needed to connect regional cerebral blood flow data to cognitive processes. Several of these assumptions can be challenged. We view our results as providing one data point relevant to differentiating models of human reasoning.

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Appendix

Sample deductive items:	Sample inductive items
If I am your father then you are my daughter I am your father You are my daughter	George was a woolly mammoth George ate pine cones All woolly mammoths ate pine cones
All Capricorn pass their exams No Aries pass their exams No Aries are Capricorn	George was a woolly mammoth George had a broken leg All woolly mammoths had a broken leg
Criminals are people Criminals are dishonest Criminals are dishonest people	The sun was blocked by clouds yesterday The sun was blocked by clouds today The sun will be blocked by clouds tomorrow
If it is Monday then George loves Mary George loves Mary It is Monday	Lithium is a poison Poisons cause vomiting in monkeys Lithium will cause vomiting in humans
All coffee drinkers commit suicide All women drink coffee No women commit suicide	Men and women drink coffee Coffee decreases suicide rates in women Coffee decreases suicide rates in men
No students are bright All women are students Some women are bright	Tyrannosaurus Rex were dinosaurs Tyrannosaurus Rex were fierce hunters All dinosaurs were fierce hunters
All men have sisters Socrates was a man Socrates had a sister	Tyrannosaurus Rex were dinosaurs Tyrannosaurus Rex laid eggs All dinosaurs laid eggs
All primates are social creatures No humans are social creatures All humans are primates	Children given pacifiers have reduced levels of IQ Pacifiers are made of latex rubber Sucking on latex rubber reduces IQ
No mammoths are huge All elephants are mammoths No elephants are huge	UFOs leave giant craters where they land There are giant crater imprints in Oregon UFOs have landed in Oregon
If Jane works hard she will pass her exam Jane works hard Jane does not pass her exam	Socrates was a great man Socrates had a wife All great men have wives
All men are boys No women are boys No women are men	Socrates was a great man Socrates had a mother All great men have mothers
All carpenters are young All woodworkers are carpenters All woodworkers are young	If Anita studies she will get a ‘A’ on the Exam Anita goes skiing instead of studying Anita does not get an ‘A’ on the exam