

Inductive & Deductive Reasoning: Integrating Insights from Philosophy, Psychology & Neuroscience

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Abstract

Reasoning is the process of evaluating given information and reaching conclusions not explicitly stated in the premises. It guides and justifies our knowledge acquisition and actions. As such it has long been of interest to philosophers, and more recently psychologists and neuroscientists. Philosophers are primarily interested in the epistemic relationship between premises and conclusions. Psychologists are concerned with the cognitive processes/mechanisms involved in drawing the inference. Neuroscientists are concerned with the neural mechanisms underwriting these processes. In this article we briefly discuss the contributions made to our understanding of inductive and deductive reasoning by each of these disciplines. Given its broad scope the review is by necessity incomplete, but we address and integrate the major issues, note the progress that has been made, and point out shortcomings and dilemmas that need to be addressed to move forward.

1.0 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) 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 firelight 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 room, 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.”

- Conan Doyle, *Scandal in Bohemia*

More mundane examples include the following: Upon being told that George is a bachelor, one automatically infers that George is not married. Or upon learning that Linda will not come to our barbecue if it rains on Saturday, and noting that it is indeed raining on Saturday, we do not set a place for her. While not as impressive as Holmes' conclusions, they emerge in a straightforward way from the provided information, and have a certainty sorely lacking in Holmes' inferences.

Reasoning has long been of interest to philosophers, and more recently psychologists and neuroscientists. Philosophers are interested primarily in the epistemic relationship between premises and conclusions, that is, they want to know the nature of the warrant the premises provide for accepting the conclusion. Psychologists are concerned with the cognitive processes/mechanisms involved in drawing the inference. Neuroscientists are concerned with the neural mechanisms underwriting these processes. In this article we briefly discuss the contributions made to our understanding of inductive and deductive reasoning by each of these disciplines. Given its broad scope the review is by necessity incomplete, but we address and integrate the major issues, note the progress that has been made, and point out shortcomings and dilemmas that need to be addressed to move the field forward.

2.0 Philosophical Issues

One major area of study for philosophy is the acquisition and justification of knowledge. Reasoning from given information (premises) to conclusions is one important source of knowledge. Therefore, it should not be surprising that the major philosophical issue in the study of reasoning is the nature of the warrant that the premises provide for accepting the conclusion. Based on this relationship, philosophers have sorted arguments into two broad categories: deduction and induction.

2.1 Deduction

Consider the following deductive arguments:

A) All men are mortal; Socrates is a man

\ Socrates is mortal.

B) All men are short; Socrates is a man

\ Socrates is short.

Deductive arguments can be evaluated for validity and soundness. An argument is valid if the premises provide absolute grounds for accepting the conclusion. Given the truth of the premises in arguments A and B, there can be no doubt about the truth of the conclusion. Validity is, however, independent of the actual truth of the propositions. Arguments A and B are equally valid, even though B contains some questionable premises which may lead to an untrue conclusion. An argument is considered sound when the premises are true and the argument is valid, as in A.

Validity is a function of the logical structure of the argument as opposed to sentence content. Consider the following examples:

C) Tweety is a Robin; no Robins are migrants;

\ Tweety is not a migrant.

D) Oxygen is an element; no elements are molecular;

\ Oxygen is not molecular.

If we give you the premises of these arguments and ask you whether the conclusion is valid, in both cases you will respond in the affirmative. Now if we turn around and ask whether you know Tweety the Robin? If you don't, how could you possibly know that he's not a migrant? Similarly, do you know enough chemistry to be certain that oxygen is not molecular? You certainly don't know Tweety the Robin, and you may or may not know enough chemistry to be certain about the status of oxygen. However, this is all beside the point. Your certainty that Tweety is not a migrant and that oxygen is not molecular arises from the logical form of the arguments, which can be written as such:

E) M has F; nothing with F has G;

\ M does not have G.

It is by virtue of this logical form, not the content of the sentences, that you can be certain the conclusion follows from the premises. You can substitute any content whatsoever into this logical form and the conclusion will still follow from the premises. The fact that validity is a function of logical form (rather than content) has made it possible to develop very sophisticated calculi for deductive inferences, which has turned the philosophical branch of deductive logic into a quasi-mathematical discipline that is heavily rule dependent.

2.2 Induction

Arguments where the premises provide only limited grounds for accepting the conclusion are broadly called inductive arguments.¹ The classic form studied is that of enumerative induction. Consider the example:

- F) Socrates was a dinosaur; the skeletal remains of Socrates reveal four legs;
- \ All dinosaurs had four legs.

This is clearly not a valid argument. The premises involve the observation of one (or a few) dinosaurs. Their truth cannot guarantee the truth of the conclusion, which involves all dinosaurs. However, most of us would be prepared to accept the argument in F as plausible or reasonable. The question is: what justifies this inference? Hume (1748/1910) famously considered this problem in the guise of causal inference. He argued that the conclusion is neither a report of direct experience nor a logical

¹ it is important to separate the use of the term 'induction' here from its use in the term "mathematical induction." Mathematical induction, despite the name, is a species of deduction.

consequence of it. It cannot be the former because we have viewed a limited number of dinosaur remains, and it cannot be the latter because an inference from the premises (or our experience) would require an appeal to a Principle of the Uniformity of Nature, where "...instances, of which we have had no experience, must resemble those, of which we have had experience, and that the course of nature continues always uniformly the same." (Hume, 1748/1910, section IV). But such a principle cannot, of course, be established by observation or deductive inference. It can only be established by inductive inference, which presupposes the principle, thus leading to a vicious circle. If Hume is correct, this negative argument rules out the possibility of justifying induction. In other words, the epistemological problem of induction is insoluble.

Despite Hume's observation, it is a fact that human beings are almost compelled to draw inferences from limited information, as in argument F. Why? Hume's positive contribution to the problem of induction is an answer to this latter question. He suggests that the experience of constant conjunction results in a "habit of mind" that leads us to anticipate the same conclusion whenever we encounter another instance of the premises (Hume, 1748, section V, part I). For example, having seen several dinosaur skeletons and noting that they all have four legs results in a "habit of mind" leading to the expectation that the next dinosaur skeleton encountered will also have four legs. On this account, the basis of induction is not to be found in some objective feature of the world, as is the case with (rule dependent) calculi for making deductive inferences, but rather in the structure of our minds. That is, he provides a *psychological solution* to the problem.

Now consider the following argument:

G) Socrates was a dinosaur; the skeletal remains of Socrates reveal a broken leg

\ All dinosaurs had a broken leg.

Most of us would not be prepared to accept the conclusion of G. Frankly, it sounds crazy. So, what is the difference between F and G such that we would accept argument F as plausible but consider argument G to be implausible? Interestingly, unlike in the case of deduction, we cannot appeal to logical form to differentiate between the plausibility of F and G because both of them have an identical logical form, namely:

H) X has the property alpha and X has the property beta

\ Everything with the property alpha has the property beta.

To state the problem in Hume's vocabulary, why does observing the regularity in finding dinosaur bones with four legs result in the formation of a "habit of mind" or expectation that all dinosaurs had four legs, but not in the expectation that all dinosaurs had broken legs? Even if every skeletal find that reveals four legs also reveals broken legs, why is the mind prepared to generalize the former regularity but not the latter?

This is the New Riddle of Induction articulated by Goodman (1955) with the famous grue example. Consider the following plausible inference:

I) Emerald x is green

Emerald y is green

etc.

\ All emeralds are green.

Goodman introduced the predicate “grue”, which applies "to all things examined before [time] t just in case they are green but to other things just in case they are blue" and not examined before time t (Goodman, 1955, p. 74). This leads to the following inference:

J) Emerald x is grue

Emerald y is grue

etc.

\ All emeralds are grue.

The dilemma is that the very same observations support the incompatible conclusions that all emeralds observed in the future will be green and all future observed emeralds will be grue. How do we select which predicate to project?

Goodman points out that while Hume was correct in appealing to "habits of mind" he failed to notice that the mind is only prepared to generalize or project certain regularities but not others. It is often said that properties that project or generalize in the required manner (like all members of a species having the same number of legs) are law-like, while those that do not project or generalize (like having a broken leg) are a matter of individual accident. But this is not particularly helpful because law-like properties are defined as those that project or generalize.

So far we have stated the problem of induction utilizing the classical form of enumerative induction, where a generalization is drawn from the observation of specific instances as in examples F through J. Induction can also involve drawing a specific conclusion from specific instances as in the following example:

K) Some cats have a broken leg; Socrates is a cat;

\ Socrates has a broken leg.

One particular form of induction, called abduction, is often singled out for special treatment (Thagard & Shelley, 1997). Abduction is a form of fallacious deductive reasoning known as affirming the consequent, as in L. It can sometimes lead to a good inductive inference.

L) All (some) cats have four legs; Socrates has four legs;

\ Socrates is a cat.

While it is possible to identify different forms of induction, it is not at all clear whether this deepens our understanding of the fundamental issues. Certainly, the core issues discussed above apply across the board.

3.0 Psychology of Reasoning

While philosophers are interested primarily in the epistemic relationship between premises and conclusions, psychologists are concerned with the cognitive

processes/mechanisms involved in drawing inferences. Psychologists have three reasons to be interested in reasoning. The first obvious reason is that humans have the ability to evaluate arguments, so cognitive psychology needs to be able to articulate the mechanisms underlying this ability. The second reason is less obvious, but much deeper. Deductive inferences underpin the information processing mechanism (be it physical symbol systems or the language of thought) cognitive scientists postulate to account for cognitive processes (J. A. Fodor, 1975; Newell, 1980a; Pylyshyn, 1984). The third reason is even more compelling: cognitive theories of every phenomenon, be it vision, categorization, or problem solving, assume/require an inductive step at certain key points. Given that psychologists are interested in cognitive mechanisms underlying logical inferences, rather than the epistemic relationship between premises and conclusions, the philosophical distinction between induction and deduction may or may not be relevant for psychology. It is an empirical question. If it turns out that different cognitive mechanisms are required to account for deductive and inductive inferences, the distinction will need to be retained at the psychological level. If, on the other hand, it turns out that the same cognitive mechanism can account for both deductive and inductive inferences, the distinction will be unnecessary at the psychological level. At the moment, most researchers (but not all) think that different cognitive mechanisms are involved in deductive and inductive reasoning. In fact, researchers studying deduction and induction constitute separate communities and use different tasks and frameworks, as reviewed below. Evans and Over (2012) provide an interesting discussion of this issue in the context of probabilistic theories of deductive reasoning (see below).

3.1 Psychology of Deduction

3.1.1 Tasks and Methods

Psychologists present subjects with logical arguments, such as M through P. In each case, subjects are then asked to exhibit their knowledge of logical relationships by either determining whether the given conclusion follows from the premises or selecting a logical conclusion from several given conclusions.

M) No lizards are felines; some felines are tigers;

\ No lizards are tigers.

N) Sally is taller than Mary; Mary is taller than Betty;

\ Sally is taller than Betty

O) If David presses the brake pedal, the car will stop.

David presses the brake pedal.

\ The car stops.

P) Either Scott will choose a black car or a blue car.

Scott does not choose a blue car.

\ Scott chooses a black car.

The forms most frequently studied by psychologists are categorical syllogisms (example M), three-term transitive relations (example N), conditional (if-then) relations (example O), and disjunctive forms (example P). The categorical syllogism tests knowledge of quantification and negation. Three-term relational arguments test knowledge of transitivity relations, while operators focus on implication (if then) and disjunction (or).

3.1.2 Findings

The basic finding is that intelligent, educated subjects make numerous mistakes in deductive reasoning. Most psychologists accept that humans are rational beings. Therefore, the enterprise is one of analyzing the pattern of mistakes subjects make and from this analysis drawing conclusions about the nature of the psychological mechanisms underlying human reasoning abilities.

Perhaps the oldest and most robust finding in the psychological literature is the content effect. In the early 20th century Mary Wilkins (1928) reported that subjects reason much more accurately when the logical conclusion of the argument is consistent with their beliefs about the world (arguments 4-6 in Table 2) than when it is inconsistent with their beliefs. Subject responses fall between these two extremes when they have no beliefs about the conclusions. This effect is extremely robust and has been replicated on numerous occasions (e.g., Evans, Barston, & Pollard, 1983; Goel & Dolan, 2003). It is also the source of the deepest puzzle in developing a psychological theory of human deduction. The dilemma it presents is the following: given that deduction is a function of the logical form of the argument (and not the content) as discussed in section 2.1 above,

how can the content of the argument have such a significant effect on our ability to reason logically?

Other errors related to the content effect include, "misidentification of the task", where subjects evaluate the truth of the conclusion rather than the validity of the argument (J. S. Evans, Handley, & Harper, 2001), and the supplementation of the given information in the premises with additional information from subjects' knowledge of the world, which leads them to draw an inference that would not follow from the original information (J. St.B. T. Evans, Newstead, & Byrne, 1993).

Human Reasoners make other common errors that are unrelated to the content effect. One such error is the "atmosphere" or "mood effect" (Woodworth & Sells, 1935), wherein subjects prefer a conclusion with an existential quantifier if one of the premises has an existential quantifier, and prefer a conclusion with a negation if one of the premises contains a negation. In another error, subjects will assume the premises are symmetrical. For example, the premise "all A are B" might be treated the same as "all B are A" (compare these to "all apples are fruit" and "all fruit are apples").

Common errors in conditional reasoning include the following: subjects accept *modus ponens* (i.e. affirming the antecedent) as valid 97% of the time but accept *modus tollens* (i.e. denying the consequent), which is equally valid, only about 65% of the time. They also accept the fallacious forms of denying the antecedent and affirming the consequent as valid about 40% of the time.

The goal of psychological theories of deductive reasoning is to explain these pattern of data.

3.1.3 Theories of Deductive Reasoning

Psychologists are engaged in the business of articulating the cognitive mechanisms underlying our ability to draw deductive inferences. They do this by examining the pattern of errors generated by subjects as they engage in deductive reasoning. Given that we have a formal theory of deductive inference, and a mechanism eminently suited for carrying out deductive inferences (physical symbol systems/classical computational systems) the most natural starting point for psychological theories of deduction is to assume that the cognitive system utilizes a similar type of mechanism and explain any deviations between expected performance and actual performance as performance errors (Noam Chomsky, 1981), due to short-term memory limitations, attention limitations, misunderstanding the task, etc.. Two major theories of reasoning, mental logic and mental models, follow this approach.

Mental logic theories (Braine, 1978; Henle, 1962; Rips, 1994) postulate that reasoners have an underlying competence knowledge of the inferential role of the closed-form, or logical terms, of the language (e.g., 'all', 'some', 'none', 'and', etc.). The internal representation of arguments preserves the structural properties of the propositional strings in which the premises are stated. A mechanism of inference is applied to these representations to draw conclusions from premises. Essentially, the claim is that deductive reasoning is a rule-governed process defined over syntactic strings. Performance factors such as short-term memory limitations, attention capacity, and misunderstanding the task can result in substandard performance.

By contrast, mental model theory (Philip Nicholas Johnson-Laird, 1983; P. N. Johnson-Laird & Byrne, 1991) postulates that reasoners have an underlying competence

knowledge of the meaning of the closed-form, or logical terms, of the language (e.g. ‘all’, ‘some’, ‘none’, ‘and’, etc.)² and use this knowledge to construct and search alternative scenarios.³ The internal representation of arguments preserves the structural properties of the world (e.g., spatial relations) that the propositional strings are about rather than the structural properties of the propositional strings themselves. The basic claim is that deductive reasoning is a process requiring spatial manipulation and search. Errors are explained by performance factors, such as using background knowledge to flesh out models, terminating search too early, and memory and attentional factors.

A third popular account, dual mechanism theory, makes a distinction between formal, deliberate, rule-based processes and implicit, unschooled, automatic processes (see chapter by Jonathan Evans in this volume). Where we have knowledge about the domain we are more likely to use the latter processes. Where we have no knowledge about the domain we must rely upon the former processes. 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 (Jonathan St. B. T. Evans & Over, 1996), conscious and preconscious processes (K. E. Stanovich & West, 2000), formal and heuristic processes (Newell & Simon, 1972), and associative and rule based processes (Goel, 1995; S. A. Sloman, 1996). The relationship among these proposals has yet to be clarified. A more recent proposal suggests that the critical distinction between the two systems is the utilization of working memory (reference).

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

³ See Newell (1980b) for a discussion of the relationship between search and inference.

The formal system utilizes working memory while the heuristic system does not.⁴ One obvious shortcoming of dual mechanism theory is that while it postulates two different systems for reasoning, it does not actually provide an account of either, in the sense that mental models and mental logic theories do.

A fourth proposal, currently referred to as the "New Paradigm" (Elqayam and Evans, 2013; Elqayam and Over, 2012; chapter by Elqayam in this volume) is based upon the study of the conditional inference (if p then q). Philosophers have long worried about the fact that the formal interpretation of the conditional, as material implication, leads to some paradoxes and does not do justice to its everyday use in natural language (Lewis, 1912).

Consider the conditional an example O: if the brakes are pressed than the car will stop. On the material implication account, either the brakes are not pressed, or the car stops. So, if we believe that the brakes are pressed we should conclude with absolute certainty that the car stops. However, some philosophers (Ramsey, 1929/1990; Stalnaker, 1968, 1970), have argued that intuition and actual natural language use of the conditional is not consistent with this interpretation. Oaksford and Chater (2007, 2009) make a similar case in the psychological literature. One influential solution has been to account for intuitions and everyday language use of the conditional by recognizing that contextual factors impact reasoners' judgments. This is the Ramsey test (Ramsey, 1929/1990). It proposes that to determine the truth of a conditional requires the hypothetical addition of the

⁴ It is unclear how a cognitive process that requires no working memory can be accommodated with in information processing theory.

antecedent to our stock of beliefs, making any modifications needed to maintain consistency, and then judging whether the consequent follows (Ramsey, 1929). For example, augmenting the antecedent in the above conditional, with the knowledge that the brakes require repair, will reduce the probability of concluding that the car will stop. Similarly, knowing that the brakes have been recently serviced will increase the probability of accepting the consequent. This has led to a probabilistic approach that handles conditionals by assigning subjective conditional probabilities (de Finetti, 1937/1964; Stalnaker 1968, 1970; Oaksford & Chater, 2007).

Thus, the natural/intuitive interpretation of O is that, given what we know, the conditional probability of a car stopping, given that the brakes are pressed, is high, say, 0.9 [$P(\text{stopping} \mid \text{brakes}) = 0.9$]. However, the probability of it stopping, given the additional knowledge that the brakes require servicing is less, say 0.6 [$P(\text{stopping} \mid \text{brakes, need servicing}) = 0.6$], and the probability of it stopping given that the brakes have recently been serviced may be, say 0.96 [$P(\text{stopping} \mid \text{brakes, serviced}) = 0.96$]. Our confidence in the conclusion is a function of the subjective probability assigned, based upon our background/contextual beliefs. Once these probabilities are signed there is a nicely developed formal mechanism (Bayesian probability theory) for drawing the inference.

The ability of contextual/additional information to affect inference is a feature of induction, but is inconsistent with our understanding of deduction (section 2.1).

Oaksford and Chater (2009) argue that such an account is necessary to explain the data.

In fact, they claim that *all* logical inference, not just conditionals, is probabilistic. The

probabilistic approach does seem to provide better coverage of some data and natural language use of the conditional. It also has the additional benefit of integrating the literature on decision-making and reasoning. However, it comes at a price. One consequence of it is that there is no such thing as deductive reasoning. That is, our competence knowledge (and basic innate intuitions) are captured by probability theory, rather than formal logics. A second consequence is that all reasoning is induction, insofar as it requires drawing upon context and selecting relevant/salient information, and determining the level of salience, to assign conditional probabilities. For example, is knowing that the car above has been recently painted, or the tires rotated, relevant to assigning the conditional probabilities? Once subjective probabilities are assigned, one can apply the probability calculus, but a complete account of deductive inference (which in the “new paradigm” needs to include contextualization) cannot be given until we have a resolution to the riddle of induction.⁵

3.2 Psychology of Induction

The philosophical analysis of induction provides psychology with two basic empirical questions that need to be answered: (i) Hume's question: what is the cognitive mechanism responsible for forming "habits of mind" from previously observed regularities (i.e., what structures of mind allow us to generalize from past experience to the future?), and (ii) Goodman's question: what are the cognitive structures and mechanisms involved in determining that a particular property is generalizable (or

⁵ See Evans and Over (2012) for a different viewpoint.

projectable) or not? While there may be no epistemological solutions to the problems of induction, we know that psychological and biological solutions do exist. The psychological problem of induction is one of discovering these solutions. Psychologists have made considerable progress with respect to the first issue, but the second remains elusive.

In fact, much of the research program of the behaviorists, focused on the study of learning, addressed the issue of how minds make connections between antecedent and consequent events. For example, when a pigeon learns to associate a certain arbitrary action (e.g., the movement of its neck one inch to the right) with the presentation of a food pellet, through repeated occurrences, it is exhibiting Hume's "habit of mind". Much of this research paradigm was concerned with how such associations could be formed and modified and extinguished. This basic mechanism of association was thought to explain all behaviors, from that of the pigeon, to language acquisition and problem-solving in humans.

Psychologists eventually realized that the mechanism of association may have limited application for human behavior (N. Chomsky, 1959). By the 1960s the behaviorist paradigm gave way to the cognitive paradigm and the association mechanism was replaced with an inference mechanism, based upon computational information processing theory (Noam Chomsky, 1981; Miller, Galanter, & Pribram, 1960; Newell & Simon, 1972). The relationship between these two mechanisms is elegantly articulated by Fodor and Pylyshyn (1988).

With respect to the question of what are the relevant or projectable properties of events and entities, psychologists are pursuing two central themes: similarity and causation. Below we discuss some of the tasks and methods utilized for this purpose.

3.2.1 Tasks and Methods

In contrast to the experimental literature on deductive reasoning, the experimental literature on induction is large and varied. Due to space limitations we will review a small aspect of the literature that explicitly solicits judgments of the strength of the relationship between premises and conclusions in arguments. Directly asking subjects to judge the strength (or plausibility) of the relationship between premises and conclusions in simple enumerative inductive inference is perhaps the most direct way of doing this. For example, given:

Q) All the swans in Central Park are white;

\ All swans are white.

subjects' intuitive judgment of the strength of the conclusion allows researchers to compare different arguments and see what is common across the ones that are judged to be more plausible than others.

A more controlled way of accomplishing the same thing is through direct comparison between arguments. Here subjects are presented with competing arguments that have been selected to vary along certain dimensions, and asked to identify which is the most plausible or strongest, as in examples R and S below. Other experimental

designs compare more complex argument forms, as in examples X and Y below, used to explore the issue of diversity. Yet others compare across pairs of arguments, as in examples AB, AC, AD, and AE below, which are used to probe the importance of the underlying causal story.

3.2.2 Findings

The findings from this body of research consist of the identification of a number of "principles" which seem to guide subjects in terms of selecting the regularities to generalize or project. These principles can be organized into two broad categories: similarity and causality. We discuss each below.

3.2.2.1 Similarity

Similarity in properties between the instances in the observation (or premises) and instances in the conclusion increases the confidence in the conclusion. Consider the following examples drawn from Heit (2007):

R) Dogs have hearts;

\ Wolves have hearts.

is judged to be a stronger conclusion than

S) Dogs have hearts;

\ Bees have hearts.

because wolves are much more similar to dogs than bees are to dogs. These types of inferences inherit/exhibit many of the features of human categorization such as typicality and asymmetry (S. Sloman & Lagnado, 2005). An illustration of the former is the following example drawn from Sloman (1998):

T) Robins have sesamoid bones;

\ Sparrows have sesamoid bones.

Is judged to be a stronger conclusion than

U) Ostriches have sesamoid bones;

\ Sparrows have sesamoid bones.

The explanation is that robins are considered more typical or central members of the category of birds than ostriches and suggests that subjects are more willing to project properties from typical or central members to the overall category than from peripheral members to the overall category.

Another related phenomenon is asymmetry in inference (S. Sloman & Lagnado, 2005), illustrated in the following example:

V) Robins have 38 chromosomes;

\ Ostriches have 38 chromosomes.

is to judged to be a stronger conclusion than

W) Ostriches have 38 chromosomes;

\ Robins have 38 chromosomes.

The explanation is that that we are more prepared to project properties from typical or central members of categories to nontypical members than from nontypical members to typical members. Because robins are more typical or central members of the category of birds than ostriches we more readily project properties from robins to ostriches than from ostriches to robins.

However, there is also a diversity effect at work (S. Sloman & Lagnado, 2005).

Subjects tend to judge the following argument:

X) Robins require magnesium to live; Ostriches require magnesium to live;

\ All birds require magnesium to live.

as stronger than

Y) Robins require magnesium to live; Sparrows require magnesium to live;

\ All birds require magnesium to live.

This suggests that instances of a property to be found in peripheral members of a category strengthens the likelihood of the property being projected to the whole category.

There are also a number of fallacies or counterexamples in this literature. For example, in the inclusion fallacy (D. N. Osherson, Smith, Wilkie, López, & Shafir, 1990), many people consider

Z) Robins have sesamoid bones;

\ Birds have sesamoid bones.

To be stronger than

AA) Robins have sesamoid bones;

\ Ostriches have sesamoid bones.

This is problematic because the first conclusion implies the second. If ostriches belong to the category of birds, even given their peripheral status, there is no reason to suspect that they do not have sesamoid bones.

3.2.2.2 Causality

An appeal to causality is the other means of differentiating between regularities that humans are prepared to project and those that they are not. The basic idea here is that generalization/projection from one instance to another instance is warranted if the same

causal laws or mechanisms underwrite both instances. For example (Heit & Rubinstein, 1994), subjects prefer the inference:

AB) Hawks have a liver with two chambers;

\ Chickens have a liver with two chambers.

to the inference

AC) Hawks have a liver with two chambers;

\ Tigers have a liver with two chambers.

This is consistent with the similarity account. However, subjects also prefer the inference:

AD) Hawks prefer to feed at night;

\ Tigers prefer to feed at night.

to the inference

AE) Hawks prefer to feed at night;

\ Chickens prefer to feed at night.

The explanation is that, inference strength is not simply a matter of similarity but rather a function of the underlying causal stories that subjects believe or assume. In the former

example, subjects are focusing on the biological properties of chickens, hawks and tigers and concluding that chickens and hawks are more closely related than hawks and tigers in terms of anatomy. In the latter example, subjects are focusing on the fact that hawks and tigers are hunters and carnivores, while chickens are not.

Causal chains can also be used to explain certain asymmetries in inference strengths. For example (S. Sloman & Lagnado, 2005):

AF) Gazelles contain retinum;

\Lions contain retinum.

is usually considered stronger than

AG) Lions contain retinum;

\Gazelles contain retinum.

The expectation is that lions eat gazelles and the digestive tract may be a possible mechanism for transmitting retinum.

Thus, what we have emerging from this line of research are series of "principles" that presumably constrain the observed regularities that humans are and are not willing to project or generalize.

3.2.3 Theories of Induction

Induction is typically viewed as a form of hypothesis generation and testing, where the crucial issue is one of searching a large database and determining which pieces of information are relevant and how they are to be mapped onto the present situation. The determination of relevance and generalization of certain properties, but not others, is guided by a series of principles or constraints such as provided by similarity and causality. The theoretical efforts in this area have been devoted to discovering these principles and incorporating them into models that can explain the varying strength of connections between premises and conclusions.

The similarity-coverage model developed by Osherson et al. (1990) is often considered the most well known mathematical model of property induction. It predicts the strength of inductive arguments based on the degree to which the premise categories resemble the conclusion category and/or the extent to which the premises account for the smallest superordinate taxonomic category that includes both the premises and the conclusion (e.g., robins use serotonin as a neurotransmitter; blue jays use serotonin as a neurotransmitter; geese use serotonin as a neurotransmitter. Since robins and blue jays have the property, it may be the case that all birds have the property. Geese are birds, so maybe geese have the property too) (Osherson et al., 1990). Sloman (1993) proposed a competing model of induction that relies on a normalized measure of feature overlap between the premises and conclusion of an argument. This feature-based model has been adapted using a feed-forward connectionist network (Rogers & McClelland, 2004). However, it has been argued that neither of these feature-based models overcomes the original limitations of the similarity-coverage model: Its inability to account for inductive arguments that cannot be expressed as pairwise similarities or taxonomic categories (e.g.,

X uses heraticulin; Y uses heraticulin; Z uses heraticulin) and its lack of a principled mathematical foundation [see (Tenenbaum, Kemp, & Shafto, 2007) for a more detailed discussion].

These models provide interesting and valuable insights. However, it is important to understand what these models do and do not explain. Most importantly, they do not explain the notion of similarity. It is a value that must be inserted into the model. One can, of course, appeal to other models that purport to calculate the similarity between two objects or events (Goldstone, Day, & Son, 2010; Tversky, 1977) but these models leave unexplained why certain properties or features are relevant, and how relevant they are. This information must be provided to the model for it to perform the calculation. This highlights the limitations of the psychological research and elusiveness of the New Riddle of Induction raised by Goodman (1955).

More generally, reviewing the state of our understanding of inductive inference at a psychological level is a humbling experience. First, with regard to similarity, while many psychologists believe that similarity is a useful explanatory concept, philosophers (Goodman, 1955) and some psychologists (S. A. Sloman & Rips, 1998) recognize that it largely begs the question. Any two objects can share an infinite number of properties.⁶ What matters for purposes of inductive reasoning is the identification of the relevant properties. The appeal to similarity was meant to explain the notion of relevance, but it seems that an independent notion of relevance is required for similarity. Also, notions of typicality and asymmetry from the categorization literature require a notion of similarity

⁶ For example, Mount Everest and my neighbor share the properties of being located more than one mile from the sun, more than 2 miles from the sun, etc... less than 100,000,000 miles from the sun, less than 100,000,001 miles from the sun, etc. See also Murphy and Medin (1985).

for their definitions, so to appeal to these properties as features of similarity is less than satisfying.

With respect to causality, there is something intuitively very right about this approach. However, the problem is that causality seems to be a projection of the mind onto the world rather than an objective property of the world. While scientists widely use the concept of causation in their informal discourse, the formal theories do not contain such a notion. This returns us to the circularity that Hume pointed out. The justification of causation requires a principle of uniformity, that itself can only be established via an inductive inference. Therefore, the appeal to causation for an understanding of induction may be less than satisfactory.

Finally, even if we were to sort out the above issues and settle on a number of principles and constraints that guide the selection of projectable predicates, we would still be left with the problem of how to determine which ones to apply in any given case. This is of course, again, the problem of induction.

Lest we despair, it is worth remembering that there is a solution to the psychological problem of induction. There does exist a mechanism (the human brain) that is capable of making such inferences. We just need to articulate the underlying principles. Perhaps we are misunderstanding or misconceptualizing the structure of the cognitive system. The underlying assumption, within much of the cognitive literature, is that of a general-purpose reasoning system with access to (in principle) all available information (J. A. Fodor, 1975; Newell, 1980a). Within this context, it is becoming increasingly clear that the problem of projectable predicates (also known as the frame problem within cognitive science) is insoluble. Perhaps what is needed is a reconceptualization of the

cognitive architecture in a way that this problem does not arise. One such reconceptualization is offered by the "massive modularity" hypothesis (Cosmides & Tooby, 1994). On this account the mind consists of hundreds, perhaps hundreds of thousands of special purpose mechanisms that are directly triggered by specific features in the environment. That is, there is a tight causal coupling (i.e., no gap) between input-output pairs. If this is correct, then our ability to respond to wide-ranging stimuli, in extremely flexible ways, is simply an illusion. While such an account is intuitively implausible, the cognitive architecture of our brains may predispose us to tight causal coupling under the illusion of flexible responding, and this account does sidestep the riddle of induction. There may be other reconceptualizations that are more in keeping with the data and our intuitions that also sidestep the problem.

4.0 Cognitive Neuroscience of Reasoning

In terms of the neuroscience of reasoning, the goal is to identify the neuronal systems and understand how they causally interact to enable us to draw various inferences. In the context of our current knowledge of brain functions, and the methodologies for studying these, this means identifying disassociations and interconnections between gross anatomical structures involved in reasoning processes. Popular psychological doctrine would have it that deduction, being analytical, is carried out by the left hemisphere, while induction, being synthetic, is a right hemisphere process. Unsurprisingly, the actual story emerging from the current research is much more complex and interesting.

4.1 Cognitive Neuroscience of Deduction

4.1.1 Tasks

The cognitive neuroscience of deduction literature has utilized the same tasks as the psychological literature (see section 3.1.1 above).

4.1.2 Findings

Given the formal nature of deductive reasoning and the incorporation of this formal mechanism in the psychological theories of deduction, early researchers expected to find a "reasoning module" for deduction (Goel, Gold, Kapur, & Houle, 1997, 1998). The major question seemed to be whether it would be a linguistic system as predicted by the mental logic theory or a visuospatial system as predicted by mental model theory (P. N. Johnson-Laird, 1994).

Over the years dozens of neuroimaging studies have been undertaken (Acuna, Eliassen, Donoghue, & Sanes, 2002; Canessa et al., 2005; Fangmeier, Knauff, Ruff, & Sloutsky, 2006; Heckers, Zalesak, Weiss, Ditman, & Titone, 2004; Houde et al., 2000; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002; Noveck, Goel, & Smith, 2004; Prado & Noveck, 2007; Baggio et al. 2016; Reverberi et al. 2012) and the overall results, if nothing else, at least suggest there is no single reasoning module. These studies have been discussed and the results qualitatively summarized in a review article (Goel, 2007) and more recently in a quantitative meta-study (Prado, Chadha, & Booth, 2011). A summary table from the former article is reproduced as Table 1. The results suggest that different brain areas are

recruited for logical reasoning depending upon factors such as type of argument (syllogisms, transitive inferences, conditionals, etc.) (Prado et al., 2011), presence of negation, the presence of unbelievable sentences, form of the argument (valid, inconsistent, indeterminate), presence or absence of content, emotional valence of content, etc. In this section we briefly summarize how brain recruitment for deductive reasoning differs based upon three manipulations: the presence or absence of content, conflict, and indeterminacy. The transitive inference examples in Table 2 serve to illustrate each of the three issues.

Table 2

4.1.2.1 Systems for Dealing with Familiar and Unfamiliar Material

To explore this issue, Goel and colleagues have carried out a series of studies, using syllogisms and transitive inferences, and holding logical form constant while systematically manipulating content of arguments (Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2001, 2003; Goel, Makale, & Grafman, 2004). These studies indicate that two distinct systems are involved in reasoning about unfamiliar and familiar material (arguments 1-3 vs. 4-9 in Table 2). More specifically, a left lateralized frontal-temporal conceptual/language system (Figure 1a) processes familiar, conceptually coherent material while a bilateral parietal visuospatial system, with some dorsal frontal involvement (Figure 1b) processes unfamiliar, nonconceptual or conceptually incoherent

material. Areas of activation common to both familiar and unfamiliar material include the left inferior prefrontal cortex (BA 44), left fusiform gyrus (BA 18), right fusiform gyrus (BA 37), bilateral basal ganglia nuclei (accumbens, caudate nucleus, and putamen), and right cerebellum.

Figure 1

The involvement of the left frontal-temporal system in reasoning about familiar or meaningful content has also been demonstrated in neurological patients with focal unilateral lesions to prefrontal cortex (i.e., parietal lobes intact), using the Wason card selection task (Goel, Shuren, Sheesley, & Grafman, 2004). These patients performed as well as normal controls on the arbitrary version of the task, but unlike the normal controls they failed to benefit from the presentation of familiar content in a meaningful version of the task. In fact, the latter result was driven by the exceptionally poor performance of patients with left frontal lobe lesions. Patients with lesions to right prefrontal cortex performed as well as normal controls. A recent patient study with frontotemporal dementia patients shows a similar dissociation between the frontal-temporal system and the parietal system using three-term transitive arguments with familiar and unfamiliar content (Vartanian, Goel, Tierney, Huey, & Grafman, 2009).

4.1.2.2 Systems for Dealing with Conflict and Belief-Bias

A robust consequence of the content effect is that subjects reason much more accurately about valid arguments involving believable conclusions and invalid arguments involving unbelievable conclusions (arguments 4-6 in Table 2) than valid arguments involving unbelievable conclusions and invalid arguments involving believable conclusions (arguments 7-9 in Table 2) (Evans, Barston, & Pollard, 1983; Wilkins, 1928; chapter by Ball and Thompson in this volume). In the former case (congruent condition), subjects' beliefs facilitate the task while in the latter case (incongruent condition) their beliefs inhibit the logical task. Within inhibitory belief trials the prepotent response is the incorrect response associated with belief-bias. Incorrect responses in such trials indicate that subjects failed to detect the conflict between their beliefs and the logical inference or they detected the conflict but failed to inhibit the prepotent response associated with the belief-bias (De Neys & Bonnefon, 2013) These belief-biased responses activate ventral medial prefrontal cortex (VMPFC) (BA 11, 32), highlighting its role in non-logical, belief-based responses. The correct response indicates that subjects detected the conflict between their beliefs and the logical inference, inhibited the prepotent response associated with the belief-bias, and engaged the formal reasoning mechanism. The detection of this conflict requires engagement of right lateral/dorsal lateral prefrontal cortex (BA 45, 46) (see Figure 2) (Goel et al., 2000; Goel & Dolan, 2003; Prado & Noveck, 2007). This conflict detection role of right lateral/dorsolateral prefrontal cortex (L/DLPFC) is a generalized phenomenon that has been documented in a wide range of paradigms in the cognitive neuroscience literature

(Caramazza, Gordon, Zurif, & DeLuca, 1976; Fink et al., 1999; Stavy, Goel, Critchley, & Dolan, 2006).

Figure 2

One very simple demonstration of this system using lesion data was carried out by Caramazza and colleagues (Caramazza et al., 1976) using two-term reasoning problems such as the following: “Mike is taller than George” who is taller? They reported that – consistent with imaging data (Goel et al., 2000; Goel & Dolan, 2003) – patients with lesions to the right hemisphere were only impaired when the form of the question was incongruent with the premise (e.g., who is shorter?).

4.1.2.3 Systems for Dealing with Certain and Uncertain Information

Cognitive theories of reasoning do not typically postulate different mechanisms for reasoning with complete and incomplete information (arguments 1, 2, 4, 6, 7, 8 vs. 3, 6, 9 in Table 2). However, patient and neuroimaging data suggest that different neural systems underwrite these inferences. Goel and colleagues (2007) tested neurological patients with focal unilateral frontal lobe lesions (see Figure 3) on a transitive inference task while systematically manipulating completeness of information regarding the status of the conclusion (i.e. determinate and indeterminate trials). The results demonstrated a double dissociation such that patients with left prefrontal cortex (PFC) lesions were selectively impaired in trials with complete information (i.e. determinate trials), while

patients with right PFC lesions were selectively impaired in trials with incomplete information (i.e. indeterminate trials). These results have been duplicated and further clarified in a recent imaging study (Goel, Stollstorff, Nakic, Knutson, & Grafman, 2009).

Figure 3.

4.1.3 Implications for Cognitive Theories of Deductive Reasoning

The major cognitive theories of deductive reasoning do not fare well with respect to the neuropsychological data. Mental models theory predicts the involvement of the visuospatial system in logical reasoning while mental logic theory predicts involvement of the language/syntactic system. The cognitive neuroscience data shows that both systems can be engaged depending on the nature of the stimuli. Dual mechanism theory predicts the involvement of two systems, an effortful formal system and an automatic reflex-type system that we share with rats and pigeons (Jonathan St. B. T. Evans & Over, 1996; K. Stanovich, 2004), and more recently, a system involving working memory and a system not involving working memory (reference). However, while the cognitive neuroscience data do show the involvement of multiple systems, one which does correspond to the effortful formal system, the other is a very sophisticated conceptual, language mediated system that we certainly do not share with rats and pigeons (Goel, 2008), nor can it operate in the absence of working memory. Finally, while there have

been no cognitive neuroscience experiments to directly test the probabilistic account of deductive reasoning, there are, nevertheless, experiments that introduce uncertainty or indeterminacy into deductive reasoning tasks and show a double dissociation between certain and uncertain inferences (section 4.1.2.3), suggesting that the brain is quite capable of engaging in both types of reasoning. So, insofar as the "new paradigm" wants to suggest that all deductive inferences contain a degree of uncertainty, this claim would seem to be inconsistent with the neuropsychological data.

More positively, the data tell us that the brain is organized in ways not anticipated by cognitive theory. In particular, there is no unitary system for deductive reasoning in the brain (be it mental model, mental logic, or probability theory). The evidence points to a fractionated system that is dynamically configured in response to certain task and environmental cues. We have reviewed three lines of demarcation above including systems for heuristic and formal processes, conflict detection/resolution systems, and systems for dealing with certain and uncertain inferences. There are undoubtedly others.

While there is considerable evidence for the existence of these systems, their time course of processing and interaction is largely unknown. One *speculative* account of how processing of arguments might proceed through these systems is presented in Figure 4. It draws upon the interplay between Gazzaniga's "left hemisphere interpreter" (Gazzaniga, 2000) and right PFC systems for conflict detection and uncertainty maintenance. The function of this interpreter is to make sense of the environment by completing patterns and filling in the gaps in the available information. We don't think the system is specific to particular types of patterns. It doesn't care whether the pattern is logical, causal, social,

statistical, etc. It simply abhors uncertainty and will complete any pattern, often prematurely, to the detriment of the organism. The roles of the conflict detection and uncertainty maintenance systems are respectively, to detect conflicts in patterns and actively maintain representations of indeterminate/ambiguous situations and bring them to the attention of the interpreter.

Figure 4.

Consider again the nine possible types of three-term transitive arguments reproduced in Table 2. Arguments (1-3) that subjects can have no beliefs about are relegated to the formal/Universal methods processing system. This system is continually monitored by a conflict detector (right dorsal lateral prefrontal cortex [DLPFC]) and uncertainty maintenance system (right ventral lateral prefrontal cortex [VLPFC]). In the case of argument (2) an inconsistency will be detected between the premises and the conclusion and an "invalid" determination made. In the case of arguments (1) and (3) there is no conflict. Further pattern completion should validate the consistency of (1) resulting in a "valid" response. In the case of (3) the uncertainty maintenance system will highlight the uncertainty inherent in the premises and inhibit the left hemisphere interpreter from making unwarranted assumptions, eventually allowing an "invalid" response to be generated.

Arguments (4-9), containing propositions that subjects have beliefs about, are initially passed on to the left frontal-temporal system for heuristic processing. However, if a conflict is detected between the believability of the conclusion and the logical response (7-9) the processing is rerouted to, or at least shared with, the formal pattern matcher in the parietal system. In the formal system these arguments are dealt with in a similar manner as arguments (1-3), except for the following important differences: (i) the conflict detection system has to continually monitor for belief-logic conflict while also monitoring for logical inconsistency; and (ii) the fact that subjects have beliefs about the content will also make the task of the uncertainty maintenance system much more difficult. Often it will fail to inhibit the left hemisphere interpreter. Both of these situations place greater demands on the cognitive system, resulting in longer reaction times and lower accuracy scores in these types of trials (Goel and Dolan, 2003).

Arguments (4-6) are passed to the left frontal-temporal heuristic/conceptual system and are largely (though not necessarily exclusively) processed by this system. The believability of the conclusion response is the same as the logical response, facilitating the conflict detection in (5) and pattern completion in (4). Even the "invalid" response in (6) is facilitated, but for the wrong reason. As above, the unbelievability of the conclusion makes it difficult for the uncertainty maintenance system to maintain uncertainty of the conclusion, but in this case failure facilitates the correct response.

The main contribution of the cognitive neuroscience literature to the study of deductive reasoning has been the fractionation of the system and the identification of some of the component parts, such as a conflict detection system, a system sensitive to conceptual content, a system sensitive to formal structure, and a system for maintaining

uncertainty. The data do not tell us anything about the internal mechanisms of these systems, or indeed, how the systems interact with each other. Nonetheless, the findings are an important first step because they identify mid-level concepts (i.e., between the level of Turing machine descriptions and phenomenological descriptions) that can be used for theory building. One way to move forward, in terms of understanding the interactions of these systems, is the development of computer programs of deductive reasoning using these concepts.

4.2 Cognitive Neuroscience of Induction

4.2.1 Tasks

The literature examining the neuroscience of induction is sparse. It perhaps begins with the split brain patient studies (Gazzaniga, 1989; Gazzaniga & Smylie, 1984) involving implicit inference tasks (see below).

More recently a few studies have focused on differential patterns of brain activation for inductive versus deductive inference (Goel & Dolan, 2004; Goel et al., 1997). These studies involve placing subjects in brain scanners and presenting them with inductive arguments (AH) in one condition and deductive arguments (AI) in another condition and asking them to make judgments of plausibility in the former case and judgments of validity in the latter case. Following are examples of inductive (AH) and deductive (AI) items used in these studies:

AH) House cats have 32 teeth

Lions have 32 teeth

\ All felines have 32 teeth

AI) All animals with 32 teeth are cats

No cats are dogs

\ No dogs have 32 teeth

A related study examined deductive versus probabilistic reasoning (D. Osherson et al., 1998) by presenting similar three-term arguments and instructing participants to decide whether the conclusion was valid or invalid (logic task) or whether it had a greater chance of being true than false (probability task):

AJ) None of the bakers play chess

Some of the chess players listen to opera

\ Some of the opera listeners are not bakers.

Other neuroimaging-based studies have examined inductive reasoning by way of analogical mapping. In one study, participants viewed pictures of colored geometric shapes and determined whether the shapes were analogous (analogy condition) or identical (literal condition) compared to a source picture of shapes (Wharton et al., 2000). Other studies have examined brain activation associated with judgment of analogous word pairs (Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006):

AK) Planet : Sun versus Electron : Nucleus

or verbal analogies (Luo et al., 2003):

AL) Soldier is to army as drummer is to band

4.2.2 Findings

In one classic experiment, a split brain patient was presented with a picture of a winter scene projected to the right hemisphere and a picture of a chicken claw projected to the left hemisphere. The patient must then select, from an array of other pictures, one picture with each hand, which two are related to the projected pictures. The patient's left hand points to a shovel (because the right-hemisphere, controlling that hand has seen a snow-covered winter scene) and the right-hand points to a chicken (because the left hemisphere, controlling that hand, has seen the chicken claw). When the patient is asked to explain why his left hand (guided by the right hemisphere) is pointing to the shovel, the left/language hemisphere has no access to the information about the winter scene seen by the right hemisphere. The left hemisphere instead responds by noting that the shovel is required to clean the chicken coop (Gazzaniga, 1989). In a simpler paradigm (Gazzaniga & Smylie, 1984) a picture of a pan is shown to one hemisphere, followed by a picture of water. When the pictures are shown to the left hemisphere, the patient can draw the causal inference of "boiling water." When the pictures are shown to the right hemisphere, the patient cannot draw the inference. These findings have been interpreted

as an indication of the left hemisphere's ability to effortlessly connect familiar facts together and make sense of the world.

The results of the few neuroimaging studies on evaluating inductive arguments generally indicate activation in large areas including the left frontal and parietal lobes. These regions overlap with the cortical regions involved in deductive reasoning with familiar material. However, evaluation of inductive arguments seems to be distinguished from the evaluation of deductive arguments by the involvement of the medial aspect of the left superior frontal gyrus (BA 8, 9) (Goel & Dolan, 2004; Goel et al., 1997; D. Osherson et al., 1998).

Similar areas of activation are found in analogical mapping and judgment tasks. Wharton and colleagues (2000) demonstrated enhanced brain activation in the medial frontal cortex (BA 8), the left prefrontal cortex (BA 6, 10, 44, 45, 46, and 47), the anterior insula, and the left inferior parietal cortex (BA 40) when subjects made analogical match judgments. Even when correctly judging analogous word pairs (example AK), Green and colleagues (2006) report enhanced activation of a left-sided network of parietal-frontal regions, most notably the left superior frontal gyrus (BA 9, 10). Examining analogous concepts (example AL), Luo and colleagues (2003) reported a network of activation in the left and right frontal lobes (BA 45, BA 47, BA 11) and left temporal lobe/hippocampus (BA 22). These areas are generally consistent with the areas of activation reported for other studies that have examined the neuroscience of induction.

4.2.3 Implications for Cognitive Theories of Inductive Reasoning

Unlike in the case of deduction, it is unclear how the cognitive neuroscience findings regarding inductive reasoning impact cognitive theories of induction. There are two obvious reasons for this. First, the data set is sparse and unsystematic. Second, and perhaps more importantly, within our current cognitive framework there can be no nonquestion begging theories of inductive reasoning without a solution to Goodman's Riddle of Induction, as discussed above (section 3.2.3).

Overall, the studies show consistent involvement of the left hemisphere, and more specifically a left prefrontal-temporal system in resolving inductive/analogical arguments. Several investigators have argued that activation in the parietal, temporal and inferior frontal lobes associated with inductive reasoning reflects the supporting cognitive processes (e.g., working memory, linguistic processing) required to effectively carry out these tasks (Green et al., 2006; Wharton et al., 2000). However, the left superior prefrontal cortex and frontal pole (i.e., BA 8, 9, 10) are consistently activated across these studies and appear to be strong candidates for important cortical region for inductive reasoning (Goel & Dolan, 2004).

Just as a neuroscience evidence is suggesting that deduction may not be unitary concept, the same may be true for induction. One line of inquiry would be to see if there are dissociations between different forms of inductive inference (e.g., instance to population, instance to instance, abduction, etc.). In other line of inquiry, would be to look for neural differences between drawing generalizations and selecting "relevant/salient" information. We would be surprised if interesting dissociations are not discovered along these lines.

5.0 Conclusion

The study of logic has preoccupied philosophers for at least 2500 years, psychologists for the past 100 years, and cognitive neuroscientists for the past 20 years. It is important to remember that the three enterprises are focused on different questions and are looking for different types of answers. The goal of this article has been to briefly and selectively review the questions they have asked and the answers they have provided.

Much more progress has been made (by each of the three disciplines) in terms of understanding deduction than induction. This is not surprising. We have a formal theory of deduction but no such theory for induction. Deductive logic has become a sophisticated formal discipline leading to new developments in mathematics and computation (Turing, 1937; Whitehead & Russell, 1927) and anticipating its own limitations (Godel, 1931/1962). The formal theory of deduction has also informed the development of sophisticated psychological theories such as Mental Logic and Mental Models theories (Braine, 1978; P. N. Johnson-Laird, 1994; Rips, 1994), which in turn have guided the cognitive neuroscience work.⁷ The cognitive neuroscience data are now questioning the adequacy and pushing the boundaries of the psychological theories. This is all as it should be.

The state of affairs for our understanding of induction is much less clear. Many philosophers (e.g. Goodman, 1955) are resigning themselves to accept that there may be no adequate solution forthcoming to the epistemological problem of induction, be it Hume's (1748) original formulation or Goodman's (1955) New Riddle. However, the

⁷ The probabilistic accounts of inference appeal to the formal apparatus of probability theory while dual mechanism theory does not actually commit to any specific mechanisms.

problems may be amenable to solutions that appeal to the structure of the mind (i.e. psychological solutions).

Indeed, psychologists (and to some extent neuroscientists) have been able to say something interesting about the mechanisms that may underlie Hume's "habits of mind" in terms of associative and inferential mechanisms (J. A. Fodor & Pylyshyn, 1988). However, the New Riddle of Induction - of selecting the relevant or "projectable" predicates - is proving much more challenging. Both the psychological theories and empirical results lack coherence and systematicity. They have been able to provide only minimal guidance to the cognitive neuroscience research on induction. In turn, this research has had a limited impact on illuminating psychological theories of inductive inference.

But despite the lack of substantive progress we do know there is a mechanism capable of engaging in inductive inference (i.e., the human brain). Our lack of success in this regard may result from a misconceptualization of our reasoning abilities. In particular, our belief that we can, in principle, access any piece of knowledge in any given situation, may be an illusion. We may not be general-purpose reasoning systems after all (Cosmides & Tooby, 1994; Gigerenzer & Goldstein, 1996). Exploring this line of thought does have some serious consequences (J. Fodor, 2000), but it may serve to dissolve the New Riddle of Induction.

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Table 1. Summary of particulars of 19 neuroimaging studies of deductive reasoning and reported regions of activation corresponding most closely to the main effect of reasoning. Numbers denote Brodmann Areas. RH = Right Hemisphere; LH = Left Hemisphere; HI = Hippocampus; PSMA = Pre-Sensory-Motor Area. Blank cells indicate absence of activation in region. "Stimuli modality" refers to the form and manner of presentation of the stimuli. Cerebellum activations are not noted in the table. Reproduced from Goel (2007).

Studies (Organized by Tasks)	Scanning Method	Stimuli Modality	Occipital Lobes		Parietal Lobes		Temporal Lobes		Basal Ganglia		Cingulate		Frontal Lobes	
			RH	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH	LH
Transitivity (Explicit)														
Goel et al. (1998)	PET	visual linguistic		19				37		yes		24, 32		45, 46
Goel & Dolan (2001)	fMRI	visual linguistic	17, 18, 19	19	7, 40	7, 40			yes	yes			6	6, 9
Knauff et al. (2003)	fMRI	auditory/ linguistic			7	7	21	21, 38					6	46, 47
Goel et al. (2004)	fMRI	visual linguistic	18, 19	18, 19	7, 40	7	21, 22, HI	21, 22, HI					11, 47	6, 9, 46, 11
Fangmeier et al. (2006)	fMRI	visual nonlinguistic			7		40					32	6	6, 9
Transitivity (Implicit)														
Acuna et al. (2002)	fMRI	visual nonlinguistic			7, 39, 40	39, 40			yes				6, 8, 9, 46	6, 8, 9, 46
Heckers et al. (2004)	fMRI	visual nonlinguistic			40	40	37, HI	37, 21	yes			24	PSMA, 6	6, 47
Categorical Syllogisms														
Goel et al. (1998)	PET	visual linguistic		18				21, 22	yes		24, 32		45, 46, 47	6
Osherson et al. (1998)	PET	visual linguistic	18, 19	18			21/22		yes	yes			45	44, 45
Goel et al. (2000)	fMRI	visual linguistic	17, 18	17, 18				21, 22, 38	yes	yes			6	6, 44
Goel & Dolan (2003)	fMRI	visual linguistic		18, 19	7		37	39	yes	yes			6	6, 44, 45
Goel & Dolan (2004)	fMRI	visual linguistic												
Conditionals (Simple)														
Novack et al. (2004)	fMRI	visual linguistic		19			7				32		6, 47	6, 47
Prado & Novack (2007)	fMRI	visual linguistic	18	17	39, 40	40							6, 45, 46	9, 46
Conditionals (Complex)														
Houde et al. (2000)*	PET	visual nonlinguistic		18				21, 37, 39	yes	yes	24	31	10, 44, 9	
Parsons & Osherson (2001)	PET	visual linguistic			7, 39, 40	7, 39, 40								
Canessa et al. (2005)	fMRI	visual linguistic	19	19	40	40			yes	yes	32	32	6, 8, 9, 10, 46	6, 8, 9, 46
Mixed Stimuli														
Goel et al. (1997)	PET	visual linguistic		19	7, 40	7, 14	21, 22	21, 22			32	32	6, 9	6, 9
Knauff et al. (2002)	fMRI	auditory/ linguistic												

Notes: *Brodmann Areas not provided by authors.

Table 2. Three-term transitive arguments sorted into nine categories.

	Determinate Arguments		Indeterminate Arguments
	Valid	Invalid	Invalid
No meaningful Content (content has no effect on the task)	City-A is north of City-B City-B is north of City-C City-A is north of City-C (1)	City-A is north of City-B City-B is north of City-C City-C is north of City-A (2)	City-A is north of City-B City-A is north of City-C City-B is north of City-C (3)
Congruent (content facilitates the task)	London is north of Paris Paris is north of Cairo London is north of Cairo (4)	London is north of Paris Paris is north of Cairo Cairo is north of London (5)	London is north of Paris London is north of Cairo Cairo is north of Paris (6)
Incongruent (content inhibits the task)	London is north of Paris Cairo is north of London Cairo is north of Paris (7)	London is north of Paris Cairo is north of London Paris is north of Cairo (8)	London is north of Paris London is north of Cairo Paris is north of London (9)

Figures

Figure 1. Figure 1. (A) Reasoning with syllogisms such as "All apples are fruit; All fruit are nutritious; All apples are nutritious" activates a left hemisphere frontal temporal system. (B) Reasoning with logically equivalent syllogisms, but without believable/familiar content, such as, "All A are B; All B are C; All A are C" activates a bilateral occipital-parietal and dorsal frontal system (Goel et al. 2000).

Figure 2. Figure 2. When there is a conflict between the validity of an argument and the believability of the conclusion, such as in the argument, "All apples are fruit; All fruit are poisonous; All apples are poisonous", the right lateral/dorsolateral PFC is activated (Goel and Dolan, 2003).

Figure 3. Brain areas of damage underlying impairment in determinate reasoning trials (Left PFC Lesions) vs. indeterminate reasoning trials (Right PFC Lesions) reproduced from (Goel et al., 2007). Lesions to left PFC impair reasoning in determinate trials, such as, "Mary is taller than Natasha; Natasha is taller than Michelle; Mary is taller than Michelle". Lesions to right PFC specifically impair reasoning in indeterminate trials, such as, "Mary is taller than Natasha; Mary is taller than Michelle; Natasha is taller than Michelle".

Figure 4. Speculative account of the processing of arguments through neural systems reproduced from (Goel, 2008). See text.

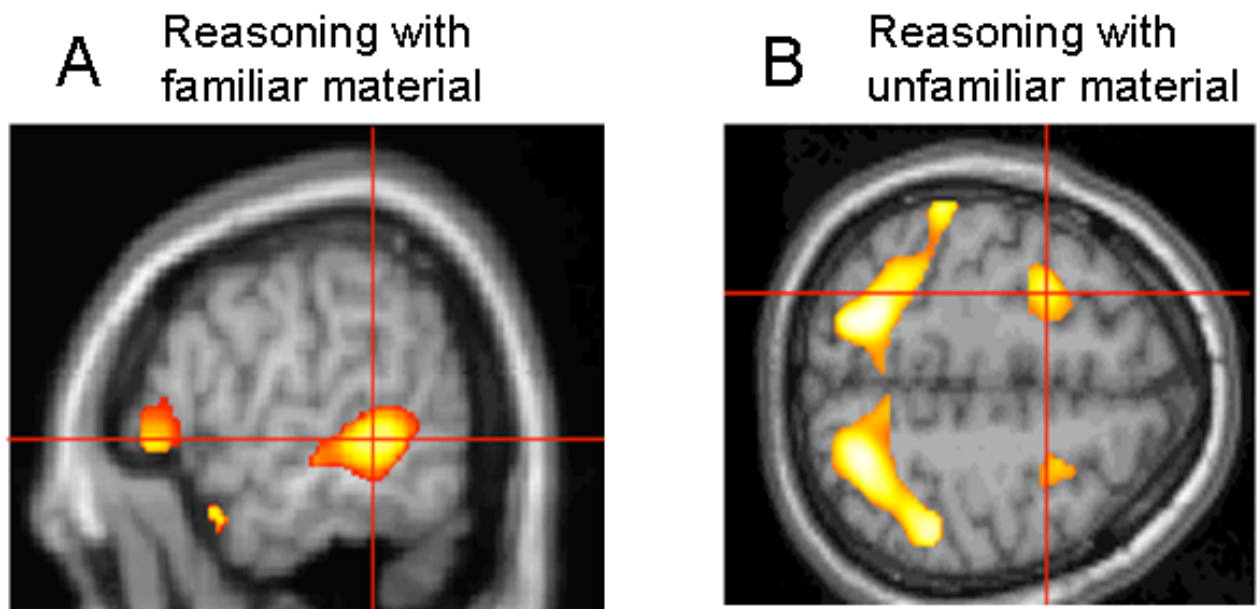


Figure 1.

Conflict detection system

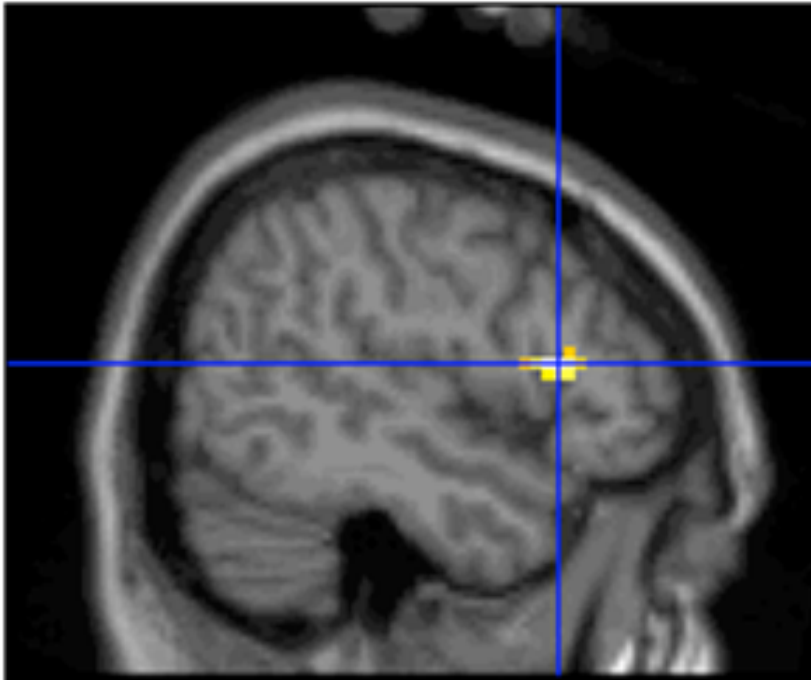


Figure 2.

Lesion Overlay Maps

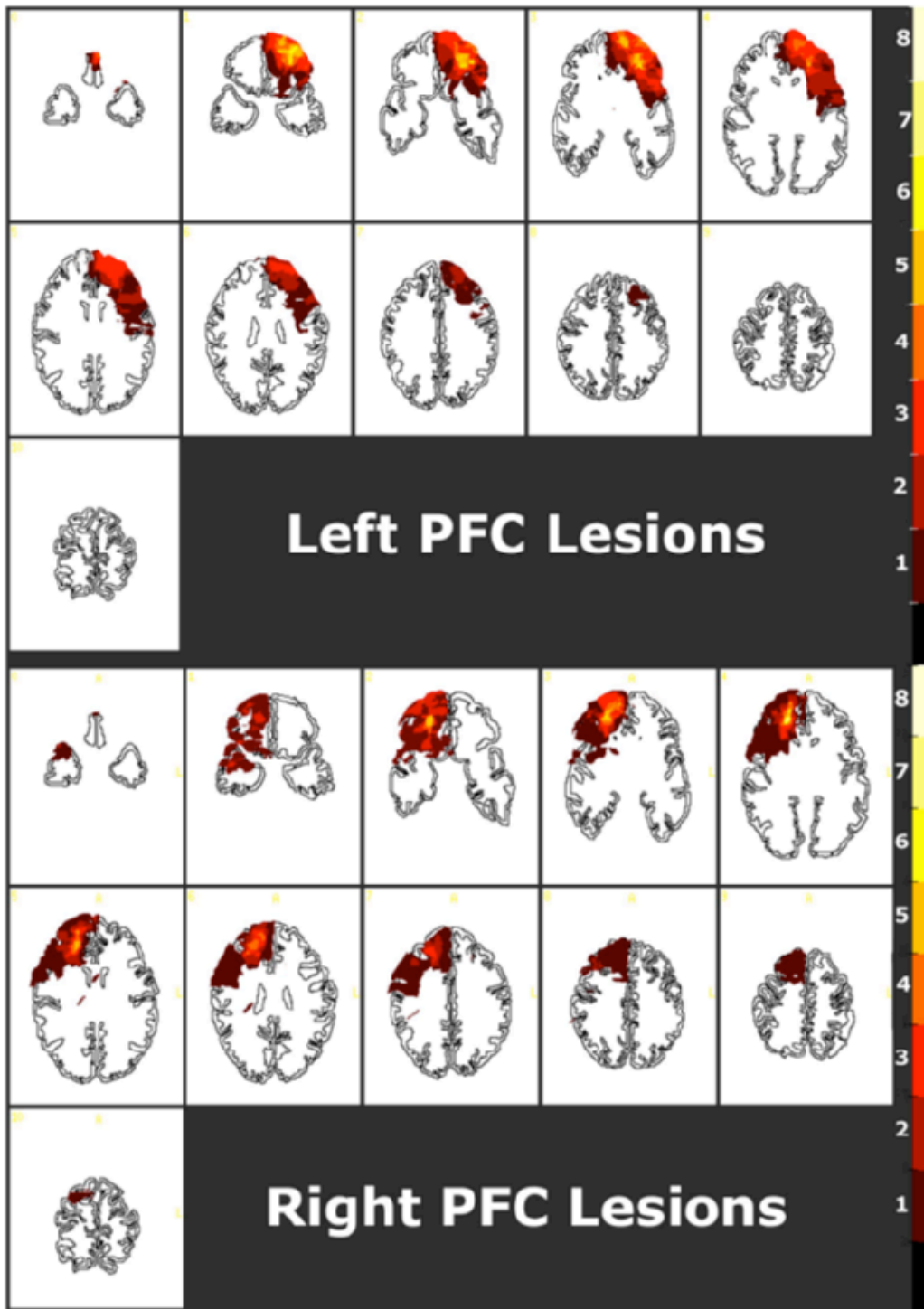


Figure 3.

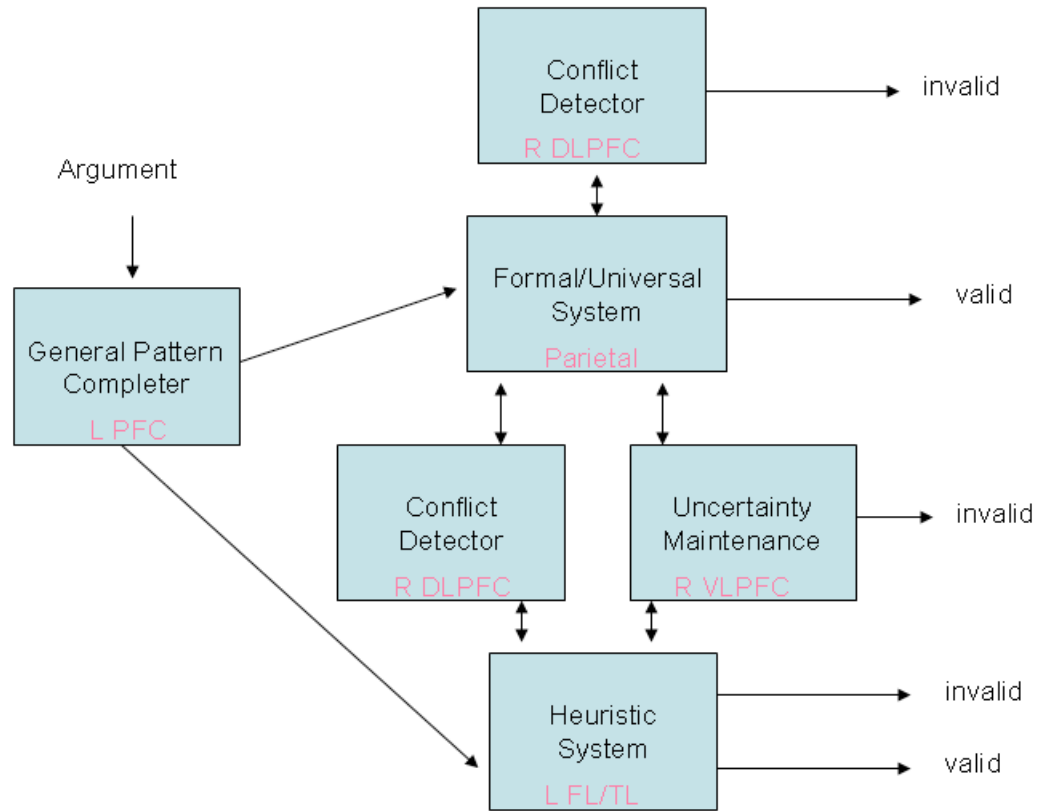


Figure 4.