Cognitive Neuroscience of Thinking

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1.0 Introduction

The study of thinking in psychology is distributed over three largely independent branches: problem solving, reasoning, and judgment and decision-making. These domains are delineated by the type of tasks they study and the underlying formal apparatus they appeal to in their explanatory framework. The problem solving literature (Newell & Simon, 1972) studies tasks such as cryptarithmetic, theorem proving, Tower of Hanoi, and also more open-ended, real-world problems such as planning, design, and even scientific induction, among others. The basic theoretical framework is one of search through a problem space using the formal apparatus of production rules (and more generally, recursive function theory). The reasoning literature (Evans, Newstead, & Byrne, 1993)is largely focused on deductive inference tasks and draws upon the formal apparatus of deductive inference. The judgment and decision-making literature (Kahneman, Slovic, & Tversky, 1988)uses such tasks as the base rate fallacy, conjunction fallacy, etc. and draws upon the formal apparatus of probability theory. The goal of these psychological enterprises is to articulate the underlying cognitive mechanisms of thinking. Unfortunately, there is little or no communications across the subdomains.

Neuropsychology, on the other hand, has focused on measuring the impact of brain injury and disease on various aspects of thinking, using IQ and memory tests, along with numerous specifically developed tasks (Lezak, 1995). Some of these tasks have directly targeted complex cognitive processes. For example, card sorting tasks (Milner, 1963), word similarity tasks, proverbs tasks (Rylander, 1939), and word definition tasks have been used to measure abstraction and generalization ability. Nonsense drawing tasks (Smith & Milner, 1988) and word generation tasks have been used to measure nonverbal and verbal fluency, respectively. Shell games have been used to measure rule/pattern induction (McCarthy & Warrington, 1990). Choice reaction time studies have been used to measure use of advance information (Alivisatos & Milner, 1989). The Tower of London has been used to measure look ahead/anticipatory abilities (Shallice, 1982) and cognitive estimation has been used to measure judgement (Shallice & Evans, 1978). Other studies have been designed to evaluate processes that may modulate complex cognitive processes. For example, Stroop-type tasks have been used to measure selective attention (Perret, 1974), while boring/monotonous tasks have been used to measure sustained attention (Wilkins, Shallice, & McCarthy, 1987). Maze tracing has been used to measure instruction following (Corkin, 1965). Drawing tasks have been used to measure perseveration (Goldberg & Bilder, 1987). The A-not-B task (Diamond, 1990) and the Antisaccade task (Roberts, Hager, & Heron, 1994) have been used to study inhibitory mechanisms.

Traditionally, there has not been a large overlap between the neuropsychology instruments and the tasks used in cognitive psychology. For example, logical reasoning tasks and judgment and decision-making tasks have been largely absent from the lesion literature. In terms of problem-solving tasks, only the Tower of Hanoi task is extensively used. However, over the past 15 to 20 years crossover fertilization between neuropsychology and cognitive psychology is beginning to alter the landscape. Neuroimaging and patient studies of reasoning (Acuna, Eliassen, Donoghue, & Sanes, 2002; Christoff et al., 2001; Goel, 2005; Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2003; Goel, Gold, Kapur, & Houle, 1997; Goel, Shuren, Sheesley, & Grafman, 2004; Houde et al., 2000; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Monti, Osherson, Martinez, & Parsons, 2007; Noveck, Goel, & Smith, 2004; Osherson et al., 1998; Parsons & Osherson, 2001; Prado & Noveck, 2007), problem solving (Cardoso & Parks, 1998; Carlin et al., 2000; Colvin, Dunbar, & Grafman, 2001; Fincham, Carter, van Veen, Stenger, & Anderson, 2002; Goel, 2002; Goel & Grafman, 1995, 2000; Goel, Grafman, Tajik, Gana, & Danto, 1997; Goel, Pullara, & Grafman, 2001; Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997; Newman, Carpenter, Varma, & Just, 2003; Owen, Doyon, Petrides, & Evans, 1996; Rowe, Owen, Johnsrude, & Passingham, 2001), and decision-making (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, Tranel, & Damasio, 2005; De Neys & Goel, in press; De Neys, Vartanian, & Goel, in press; Fellows & Farah, 2003; Glimcher, 2002; Manes et al., 2002; Paulus et al., 2001; Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003; Tranel, Bechara, & Denburg, 2002; Wolford, Miller, & Gazzaniga, 2000) have generated considerable data on the neural systems underlying these processes.

A direct review of this literature would consist of lists of neural activations associated with the different tasks in the various studies. While this may be of some pedagogical value, it is not clear that it would deepen or enrich our understanding of the underlying cognitive systems. (Goel (2007) provides such a summary for the deductive reasoning literature.) My goals, in this review, are somewhat different. I want to (1) discuss neuropsychology's contributions to the three domains within a common framework and (2) do so in a way that is relevant and informative to the development of cognitive theories of thinking.

In terms of the former goal, I propose to organize the data generated from these recent neuroimaging and lesion studies into the following three themes derived from the behavioral literature on reasoning, decision-making, and problem solving: (i) heuristics versus formal/Universal methods; (ii) conflict detection and inhibition; and (iii) Ill-structured versus well-structured situations. These themes crop up in each of the three areas, to varying degrees. In terms of the latter goal, I have previously argued (Goel, 2005) that the most immediate and valuable contribution that cognitive neuroscience can make to the understanding of cognitive processes is not in terms of listing a series of neural activations but in terms of identifying double dissociations (see Appendix A). Double dissociations are indicative of causal joints in the neural machinery (Shallice, 1988) that cognitive theories will ultimately need to respect. Putting these two aspects together I will argue that the neuropsychological evidence indicates dissociations respecting the three themes identified from the cognitive literature suggesting that these themes/issues pick out real causal joints in the neural machinery that cognitive theories will need to respect. As such, the review will be selective and non-exhaustive.

Heuristics Versus Formal/Universal Processes

The distinction between heuristic and formal/universal processes is an important, common theme in the problem solving, decision making, and reasoning literatures. Within the modern cognitive literature a useful place to begin tracin F. or g the distinction is with Simon's notion of Bounded Rationality (Simon, 1981, 1983) and the incorporation of this idea into Newell & Simon's (1972) models of human problem solving. The key idea was the introduction of the notion of the problem space, a computational modeling space shaped by the constraints imposed by the structures of a time and memory bound serial information processing system and the task environment. The built-in strategies for searching this problem space include such content free universal methods as Means Ends Analysis, Breath First Search, Depth First Search, etc. But the universal applicability of these methods comes at the cost of enormous computational resources. But given that the cognitive agent is a time and memory bound serial processor it would often not be able to respond in real time, if it had to rely on formal, context independent processes. So the first line of defense for such a system was the deployment of task-specific knowledge to circumvent formal search procedures.

Consider the following example. I arrive at the airport in Paris and need to make a telephone call before catching my connecting flight in an hour. I notice that the public telephones require a special calling card. The airport is a multistory building with shops on several floors. If I know nothing about France I could start on the top floor at one end of the building, enter a store and ask for a telephone card. If I find one, I can terminate my search and make my phone call. If I don't, I can proceed to the next store, until I have visited every store on the floor (or found a telephone card). I could then go down to the next floor and continue in the same fashion. Following this breadth first (British Museum) search strategy, I will systematically visit each store and find a telephone card if one of them sells it. The search will terminate when I have found the telephone card, or visited the last store. This may take several hours, and I may miss my connecting flight. If however, I am knowledgeable about France, I may have a specific piece of knowledge that may help me circumvent this search: Telephone cards are sold by the Tabac Shop. If

I know this, I merely have to search the directory of shops, find the Tabac shop and go directly there, circumventing the search procedure. Notice this knowledge is very powerful, but very situation specific. It will not help me find a pair of socks in Paris or make a telephone call in Delhi.

On this account, heuristics are situation specific, learned and consciously applied procedures, not the type of things one makes a science out of. So not surprisingly, much of the subsequent research effort of this program was devoted to developing formal search algorithms and computational constraints on cognitive architecture (Newell, 1990) rather than heuristic procedures.

The work of Tversky and Kahneman (1974) in the judgment and decision making literature can be viewed as a development of the heuristic branch of the cognitive system. Perhaps their most important contribution was the identification of a number of content general "biases" or fallacies that we are all subject to, such as the conjunction fallacy and base rate fallacy (Gilovich & Kahneman, 2002; Kahneman et al., 1988; Kahneman & Tversky, 1996). Here is an example of the latter (Kahneman & Tversky, 1973):

A psychologist wrote thumbnail descriptions of a sample of 100 participants consisting of 15 engineers and 85 lawyers. The description below was chosen at random from the 100 available descriptions.

Jack is a 45-year old man. He is married and has four children. He is generally conservative, careful, and ambitious. He shows no interest in political and social issues and spends most of his free time on his many hobbies which include home carpentry, sailing, and mathematical puzzles.

Which one of the following two statements is most likely?

a. Jack is an engineer.

b. Jack is a lawyer.

c. Equally likely that Jack is an engineer or lawyer.

In such problems, the correct normative answers are given by the base rates, so the response should be (b) in the above example. However, the accompanying description engages heuristic processes that often override the normative response, so many subjects will respond (a) based on the description (Kahneman & Tversky, 1973). Tversky and Kahneman identified several heuristics including representativeness, availability, and anchoring and adjustment to explain such fallacies. The one at work in the above example is "representativeness". The description is more representative of a typical engineer than a lawyer and this overrides the base rate information.

Similar phenomenon have been identified in the logical reasoning literature under the guise of the belief-bias effect. It is the case that logical arguments with believable conclusions are accepted much more readily than arguments with unbelievable conclusions (Wilkins, 1928). For example, the following valid argument with a believable conclusion is accepted as valid 96% of the time:

No cigarettes are inexpensive;

Some addictive things are inexpensive ;

∴ Some addictive things are not cigarettes.

By contrast, a logically identical argument, but with an unbelievable conclusion, is accepted as valid only 46% of the time (Evans, Barston, & Pollard, 1983):

No addictive things are inexpensive;

Some cigarettes are inexpensive;

∴ Some cigarettes are not addictive.

The explanation is that instead of engaging in formal logical analysis, subjects are falling victim to a believability heuristic which leads them astray in this particular case (Evans, 2003; Evans & Over, 1996; Sloman, 1996).

While there are some interesting and important differences --in terms of ontological commitments -- in the development of these ideas in the three literatures, they are beyond the scope of this review. The important point for our purposes is the distinction between using knowledge and beliefs to solve a problem versus using more general or "universal", content free procedures. This is an important theme in all three areas under consideration.

The neuropsychological data provides compelling evidence for these two systems in terms of double dissociations respecting the distinction. In the balance of this section I will review studies where the experimental design involve the manipulation between heuristic and formal strategies. In the next section studies involving explicit conflict between the two strategies are considered.

Perhaps the most extensive evidence for anatomical dissociation along the heuristic and formal dimension comes from neuroimaging work on deductive reasoning.

Goel et al. (2000) presented subjects with logical arguments containing familiar content (i.e. propositions that they would have beliefs about) such as:

All dogs are pets;

All poodles are dogs;

∴ All poodles are pets

and logically identical arguments lacking any meaningful content (i.e. subjects can have no beliefs about the truth or falsity of these propositions) such as:

All P are B;

All C are P;

∴ All C are B

These studies indicate that two distinct systems are involved in reasoning about familiar and unfamiliar material. More specifically, a left lateralized frontal-temporal conceptual/language system processes familiar, conceptually coherent material, corresponding to the heuristic system, while a bilateral parietal visuospatial system processes unfamiliar, nonconceptual material, corresponding to the formal/universal system (see 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 (parietal lobes intact) using the Wason card selection task (see Figure 2) (Goel, Shuren et al., 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 the meaningful version of the task. In fact, consistent with the neuroimaging data, 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 for as well as normal controls.

There is even some evidence to suggest that the response of the frontal-temporal system to familiar situations may be content specific to some degree (in keeping with some content specificity in the organization of temporal lobes) (McCarthy & Warrington, 1990). One source of evidence comes from a study involving landmarks in familiar and unfamiliar environments (Goel, Makale, & Grafman, 2004). Arguments such as:

"Paris is south of London;

London is south of Edinburgh;

∴ Paris is south of Edinburgh"

involving propositions that subjects would have beliefs about (as confirmed by a post-scan questionnaire), were compared with arguments such as:

"The AI lab is south of the Roth Centre;

Roth Centre is south of Cedar Hall;

∴AI lab is south of Cedar Hall"

containing propositions that subjects could not have beliefs about because they describe a fictional, unknown environment.

These stimuli not only resulted in a dissociation between a frontal temporal system for the familiar propositions and a parietal system for the unfamiliar environments, the temporal lobe activation in the former case included posterior hippocampus and parahippocampal gyrus, regions implicated in spatial memory and navigation tasks. These data provide support for the generalization of the above results to transitive reasoning and indicate variability in temporal lobe activation as a function of content. Perhaps the most studied example of content specificity in the organization of the heuristic system is the "Theory of Mind" reasoning system identified by a number of studies (Fletcher et al., 1995; Goel, Grafman, Sadato, & Hallet, 1995).

There is at least one study (De Neys & Goel, in press) that suggests a similar breakdown for problems from the decision making literature, in particular the "Lawyer-Engineer" base rate problems described above. Participants were scanned while they were solving classic "Lawyer-Engineer" problems. Results showed that, just as during deductive reasoning, belief-mediated decisions based on stereotypical descriptions activate a left temporal lobe system whereas a bilateral parietal system is activated when the response is in line with the base rates.

While the hypothesis for dissociation of heuristic and universal/formal processes at the neural level has not been tested directly with tasks from the problem solving literature, there is at least some suggestive data, and at least one theory of frontal lobe functioning predicts that this should be the case. Grafman (2002; Wood & Grafman, 2003) has long maintained that prefrontal cortex is critical for the storage and retrieval of large-scale knowledge structures generally called "scripts". Scripts guide our behavior in daily, routine situations like going to work, ordering a meal at the restaurant, going shopping, etc.. There are many studies showing patients with lesions to prefrontal cortex often show greater impairment in problem-solving tasks involving real-world knowledge than in the more abstract neuropsychological test batteries. One such task tapping simple real-world knowledge is the Scripts task (Sirigu, Zalla, Pillon, Grafman, Agid et al., 1995; Sirigu, Zalla, Pillon, Grafman, Dubois et al., 1995). In this task subjects are given familiar situations and asked to list what they would do. For example, "you're going on a date tonight, list all the things that you would do". The responses of patients are compared with the normed response of normal controls. Patients with lesions to prefrontal cortex have greater difficulty with this type of task than would be anticipated by their neuropsychological testing profile.

However, the interpretation of these data is complicated by the fact that real-world problems and neuropsychological test batteries differ on many dimensions (including task structure, which is discussed below), not just the presence of real-world knowledge. Ideally, what is required is a task that can be undertaken in a condition where the subject's real-world knowledge is very relevant and another condition where it is less relevant. I'm unaware of such manipulation in the neuropsychology literature.

Conflict Detection/Inhibition

A natural consequences of dual systems/processes is potential for conflict and facilitation between the two systems. For example, in the case of logical reasoning, given arguments such as

All apples are fruit;

All fruit are poisonous;

All apples are poisonous.

There is a conflict that arises between the validity of the argument and the truth of the conclusion (valid but false conclusion). A robust consequence of the content effect is that subjects perform better on reasoning tasks when the logical conclusion is consistent with their beliefs about the world than when it is inconsistent with their beliefs (Evans et al., 1983; Wilkins, 1928)

A very similar situation arises in many decision-making tasks. Consider the base rate fallacy task above. The base rates point to one response (95% chance that Jack is a lawyer) while the description of Jack is more prototypical of an engineer. This generates a conflict that the subject must recognize and resolve. Is the description sufficiently poignant/salient to overcome the odds in this particular instance?

The Rectangle and Polygon Task (Stavy, Goel, Critchley, & Dolan, 2006) provides an example from the problem solving literature. In this task subjects are shown a rectangle followed by a polygon derived from the rectangle by a minor modification (see Figure 3). They are asked to compare the perimeters of the two figures and determine whether the second is larger than the first. In some trials (congruent condition), the perimeter and area change in the same direction (i.e. both increase or decrease as a result of the modification). In other trials (incongruent condition), the area changes but the perimeter stays the same (for example, when a small square is removed from the upper right hand corner of the triangle). Young adults accurately respond to the congruent trials but many (46%) claim that the perimeter of the derived polygon in the incongruent condition is smaller than that of the original rectangle (Stavy et al., 2006). They explain this response in terms such as "a corner has been taken away", suggesting they're using a strategy that might be referred to as "more A (area) = more B (perimeter)". The data suggest that they do the task by attending to both the area and perimeter of the rectangle. But for most subjects, the area seems to be the more salient feature. In the congruent condition both processing streams result in the same response. In the incongruent condition a conflict arises between the responses generated by processing the area and the perimeter. To generate a correct response in this condition, the conflict must be detected and the salient response based on the area must be inhibited.

The neural basis of conflict detection issue has been extensively explored within the reasoning domain. Within inhibitory belief trials the prepotent response is the incorrect response associated with belief-bias (e.g. all children are nasty; all nasty people should be punished; all children should be punished). Incorrect responses in such trials indicate that subjects failed to detect the conflict between their beliefs and the logical inference and/or inhibit the prepotent response associated with the belief-bias. These belief-biased responses activate ventral medial prefrontal cortex (BA 11, 32), highlighting its role in non-logical, belief-based responses (Goel & Dolan, 2003). 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 4) (Goel et al., 2000; Goel & Dolan, 2003; Prado & Noveck, 2007). This conflict detection role of right lateral/dorsal prefrontal cortex is a generalized phenomenon that has been documented in a wide range of paradigms in the cognitive neuroscience literature (Fink et al., 1999;

Picton, Stuss, Shallice, Alexander, & Gillingham, 2006; Vallesi, Mussoni et al., 2007; Vallesi, Shallice, & Walsh, 2007).

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

The involvement of right lateral/dorsolateral prefrontal cortex in conflict detection in decision-making tasks is illustrated by De Neys et al. (in press). They scanned normal healthy volunteers with fMRI while participants engaged in the lawyer-engineer type base rate problems (introduced above). As in the reasoning paradigm, activation of right lateral prefrontal cortex was evident when participants inhibited the stereotypical heuristic responses and correctly completed the decision making task.

In terms of problem-solving tasks, there are several relevant examples one can choose from, though the results are more mixed. Above we introduced the rectangle and polygon task. Neuroimaging studies of this task (Stavy et al., 2006) found activation in bilateral prefrontal cortex in the incongruent condition compared to the congruent condition, where the conflict between two strategies needs to be detected and overcome.

A second example of the role of right prefrontal cortex and content detection of is provided by Reverberi et al. (2005). They carried out a revised version of the Brixton Task with neurological patients with focal lesions. In the first half of this task subjects are presented with a series of cards, one at a time. Each card contains a 2 x 5 matrix of numbered circles. One circle on each card is colored blue, the others are white. The position of the blue Circle moves from card to card following one of seven rules. The rule is switched every five to seven cards without warning. Upon being presented with a card of the subject's task is to indicate the position of the blue Circle on the next card, thus indicating their ability to induce the current rule. The second half of the task is similar to the first, except for the following important differences: (i) rules stay active for six to 10 trials and (ii) before the end of the particular series of rule an interfering rule is introduced. This consists of sequence of four cards from the first part (only they contain red-filled circles rather than blue ones). These four cards follow a previously presented rule, but different from the current rule thus introducing a conflict between the interfering rule and the previously active rule. This conflict must be detected, the interfering rule inhibited and response generated based on the active rule. They report that while patients with lesions to left prefrontal cortex show an impairment in rule induction, patients with lesions to right prefrontal cortex are impaired specifically in the rule-conflict condition.

Ill-Structured and Well-Structured Situations

The issue of ill -structured and well-structured task environments or situations has been a crucial point of debate and contention in the problem solving literature for 40 years. The distinction originates with Reitman (1964). Reitman classified problems based on the distribution of information within the three components (start state, goal state, and the transformation function) of a problem vector. Problems where the information content of each of the vector components is absent or incomplete are said to be ill-structured. To the extent the information is completely specified, the problem is well-structured.

A mundane example of an ill-structured problem is provided by the task of planning a meal for a guest. The start state is the current state of affairs. While some of the salient facts are apparent, it is not clear that all the relevant aspects can be immediately specified or determined (e.g. how hungry will they be?; how much time and effort do I want to expend? etc.). The goal state, while clear in the broadest sense (i.e. have a successful meal), cannot be fully articulated (e.g. how much do I care about impressing the guest?; should there be 3 or 4 courses? ; would salmon be appropriate?; would they prefer a barbecue or an indoor meal?; etc.). And finally, the transformation function is also incompletely specified (e.g. should I have the meal catered, prepare it myself, or ask everyone to bring a dish?; if I prepare it, should I use fresh or frozen salmon? etc.).

Well-structured problems are characterized by the presence of information in each of the components of the problem vector. The Tower of Hanoi (see Figure 5) provides a relevant example (Goel & Grafman, 1995). The start state is completely specified (e.g. the disks are stacked in descending order on peg 1). There is a clearly defined test for the goal state (e.g. stack the disks in descending order on peg 3). The transformation function is restricted to moving disks within the following constraints: (1) Only one disk may be moved at a time. (2) Any disk not being currently moved must remain on a peg. (3) A larger disk may not be placed on a smaller disk.

Goel (1995) has extended Reitman's original characterization along the number of dimensions and articulated the cognitive consequences of these differences. In particular, it has been argued that qualitatively different cognitive and computational machinery is required to deal with Ill-structured and well-structured situations/problems. On the other hand, it has also been argued that there are no qualitative differences between ill- and well-structured problem situations and that the information processing theory machinery developed to deal with well-structured problems can also account for Ill-structured problems (Simon, 1973). The neuropsychological data, however, supports the distinction.

These issues can also arise in the reasoning and decision-making literatures, though they have not garnered equivalent attention in these domains. The most natural place for ill-structured situations in the reasoning literature is in induction tasks, where, by definition, the information provided in the premises always under determines the conclusion. However, subjects often make assumptions that eliminate uncertainty from the conclusion. For example, consider the following argument: "Sand can be red; the planet Mars is red; the sand on Mars is red." In pilot studies some subjects confidently responded "no" to this argument. When asked to explain, they made responses such as "there is no sand on Mars."

Deductive reasoning (when undertaking by nonexperts) is a prototypical example of a well-structured task. However, there are certain logical forms that result in indeterminate conclusions. For example, given A>B and A>C what is the relationship between B & C? Technically this is <u>not</u> an ill-structured inference. Any proposed relationship between B & C is undetermined and therefore invalid. However, it may not be construed as such by subjects. Cognitive theories of reasoning do not make much of this and treat these indeterminate forms in the same way as determinate forms (A>B; B >C; A >C). The neuropsychological data discussed below suggests otherwise.

In terms of tasks from the decision-making literature, elements of ill-structured situations would arise where the information was inconclusive. For example, a base rate problem with the base rate of 50:50 and ambiguous or neutral descriptions would result in an ill-structured problem. To my knowledge these types of conditions have not been explored in the decision-making literature.

There is an interesting puzzle in the neuropsychology literature that I believe can be explained in terms of the different cognitive resources required to deal with ill-structured and well-structured problems (Goel, 1995). A subset of patients with frontal lobe lesions performed very well on neuropsychological test batteries (including IQ and memory measures) but encounter serious problems in coping with real-life situations. Such cases have been documented by Shallice and Burgess (1991), Eslinger and Damasio (1985), Goel and Grafman (2000), among others. Each has offered a different explanation for the phenomenon.

Damasio (1994) argues that the cause of this difficulty is the patient's inability to inform cognitive processes by visceral, noncognitive factors. Grafman's (1989) underlying intuition, already mentioned above, is that the crucial issue is patients' inability to perform in routine, over-learned situations. His structured-event complex (SEC) theory proposes that much of our world knowledge is stored in script-like data structures and frontal lobe patients have difficulty in accessing/retrieving these structures.

Shallice (1988) suggests that the key deficit in frontal lobe lesion patients is dealing with task novelty. The idea is that there is a built-in contention scheduler that determines responses in over learned, routine situations. However, when the organism is confronted with a novel situation, the contention scheduler is unable to cope. At this point, control passes to the more sophisticated supervisory attentional system (SAS), which is damaged in frontal lobe patients, rendering them incapable of coping with novel situations.

Goel (2002; Goel, Grafman et al., 1997) has argued that neuropsychological test batteries contain largely well-structured problems while problems encountered in real-life situations contain both ill -structured and well-structured components. Given that different cognitive mechanisms are required to deal with the two situations there may be an anatomical dissociation corresponding to the cognitive and computational dissociations.

In particular, I am suggesting that when the task environment contains either facilitative patterns (real or imaginary) that can be locked onto and extrapolated for successful solution, or at least does not contain built-in hindrances to pattern extraction, the left prefrontal cortex may be necessary and sufficient for task solution. However, in cases where the start state pattern obstructs/hinders or totally under specifies a solution path through the problem space, the left hemisphere interpreter may prematurely lock on to erroneous solutions. In such situations the right prefrontal cortex plays a necessary role in generating possibilities that can aid in navigating through the problem space. It does so by supporting the encoding and processing of ill-structured representations that facilitate lateral transformations (Goel, 1995).

An apt example of the patient profile under discussion is provided by Goel and Grafman's (2000) patient PF. PF was an accomplished professional architect with a right prefrontal cortex lesion. This patient scored 128 on the WAIS-R, but was simply unable to cope in the world. At age 56 he found himself unemployable and living at home with his mother. Because the patient was an architect, they devised a task that required him to develop a new design for a lab space. His performance was compared to two age- and education-matched controls (an architect and a lawyer). The patient had superior memory and IQ and understood the task, and even observed that "this is a very simple problem". His sophisticated architectural knowledge base was still intact and he used it quite skillfully during the problem structuring phase. However, the patient's problem solving behavior differed from the controls' behavior in the following ways: (i) he had difficulty in making the transition from problem structuring to problem solving; (ii) as a result preliminary planning did not start until two thirds of the way into the session; (iii) the preliminary planning phase was minimal and erratic, consisting of three independently generated fragments; (iv) there was no progression or lateral development of these fragments; (v) there was no carryover of abstract information into the preliminary planning or later phases; and (vi) the patient did not make it to the detailing phase. This suggests that the key to understanding this patient's deficit is to understand the cognitive processes and mechanisms involved in the preliminary (ill-structured) planning phase.

Another relevant example comes from the "predicaments task" (Channon & Crawford, 1999). Channon and Crawford (1999) presented subjects (patients with anterior lesions, posterior lesions, and normal controls) with stories of every day awkward situations or predicaments such as the following:

"Anne is in her office when Tony comes in. She asks how he is, and he says he is all right, but tired. She agrees that he looks tired, and asks what is the matter. He has new neighbors who moved into the flat above his a couple weeks ago. They are nice people, but they own dogs and keep them in their kitchen at night, which is directly above Tony's bedroom. All night, and every night since they moved in, the dogs jump around and bark. He finds it impossible to get to sleep. He says he has had a word with the neighbors, and although they were very reasonable, they said they had nowhere else to put the dogs as it is a block of flats."

Subjects were required to generate solutions to these scenarios. Even though this may be an "everyday" situation, it is very clearly an ill-structured situation. Subjects also carried out more abstract neuropsychological tests which would satisfy the definition of well-structured problems. Patients as a group were impaired relative to the normal controls in both the everyday "predicaments" task and the more abstract neuropsychological tests. Patients with anterior lesions were impaired in more aspects of the "predicaments" task than the posterior patients.

Ill-structured problems do not easily lend themselves to the technical constraints of brain imaging studies. To get around this difficulty Goel and colleagues have tried to simulate specific aspects of ill-structured problems within well-structured problems. In one such attempt they manipulated the constraints on the search space of an anagram task (Vartanian & Goel, 2005). On unconstrained trials subjects were required to rearrange letters to generate solutions (e.g. generate a word from IKFEN). On semantically constrained trials they were required to rearrange letters to generate solutions within particular semantic categories (e.g. generate a word for a kitchen utensil from IKFEN). On baseline trials they rearranged letters to make specific words (e.g. generate the word 'knife' from IKFEN). The critical comparison of unconstrained vs. semantically constrained trials revealed significant activation in areas including the right ventral lateral prefrontal cortex (see Figure 6), left superior frontal gyrus, frontal pole, right superior parietal lobe, right post central gyrus, and the occipital-parietal sulcus. They argued that the activation in right ventral lateral prefrontal cortex is related to hypothesis generation in unconstrained settings, whereas activation in other structures is related to additional semantic retrieval, semantic categorization, and cognitive monitoring processes. These results extend the lesion data by demonstrating that an absence of constrains on the solution space is sufficient to engage right *ventral lateral* prefrontal cortex in hypothesis generation tasks, even in a linguistic task.

As noted above, while deductive reasoning is probably the prototypical example of a well structured task for most people, indeterminate trials do allow for situations of incomplete information. Goel et al. (2007) tested neurological patients with focal unilateral frontal lobe lesions 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 lesions were selectively impaired in trials with complete information (i.e. determinate trials; e.g. A>B, B>C, A>C; and A>B, B>C, C>A), while patients with right prefrontal cortex lesions were selectively impaired in trials with incomplete information (i.e. indeterminate trials; A>B, A>C, B>C) (see Figure 7). These findings are very similar to those of the problem solving tasks.

As noted above, while it is possible to have ill-structured situations within decision-making task paradigms, I am unaware of any studies that have addressed this issue.

Summary and Conclusion

In this chapter I've attempted to provide a selective, conceptually motivated review of cognitive neuroscience's contributions to the understanding of thought processes (i.e. reasoning, problem solving, and decision-making). The strategy has been to select three issues (heuristic versus formal processes, conflict detection/inhibition, and ill-structured and well-structured task situations) that have played important roles in the development of cognitive theories of thinking processes and suggest that these behavioral/functional distinctions correspond to distinctions in the underlying neural machinery. The exercise is valuable for at least three reasons.

First, the identification of dissociations corresponding to functional/behavioral distinctions reinforces those distinctions and provides support for cognitive theories that respect them. Second, the fact that the dissociations involved similar anatomical structures in reasoning, problem solving, and decision-making tasks (see Table 1) suggests a degree of underlying similarity or unity in these task domains at the anatomical level that is often ignored at the cognitive level.

Finally, the strategy of identifying dissociations may help to provide much needed mid-level constructs for our theories of thinking. Current theories of thinking operate at the level of either phenomenological descriptions or computational descriptions. A well-known example of the latter was introduced above in terms of the problem space construct (Newell & Simon, 1972). While this provides some critical constraints in terms of theoretical vocabulary, short-term memory limitations, and sequential processing, it is essentially a Turing machine-level description. What is missing from our theories are mid-level constructs that connect the phenomenological description to the Turing Machine - level description.

I'm suggesting that the dissociations that have been identified by lesion and neuroimaging studies--namely a formal pattern matcher, a content sensitive pattern matcher, the conflict detection system, and a system for maintaining uncertain information-- are good candidates for these mid-level systems or constructs. The first two systems may be part of Gazzaniga's "left hemisphere interpreter" (Gazzaniga, 1985, 2000). The function of the "interpreter" is to make sense of the world by completing patterns (i.e. filling in the gaps in the available information). I suspect that this system does not 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". While there is considerable evidence for the existence of such systems, their time course of processing and interactions are largely unknown. One account of how these systems may interact in the case of logical reasoning appears in Goel (in press).

Appendix A

Role of Neuropsychological Data in Informing Cognitive Theories

While few cognitive psychologists today question the value of neuroimaging and lesion data, there is still a lack of consensus as to their role in informing cognitive theory. I think they have at least two immediate roles: localization of functions and of the dissociation of functions. Arguably the latter is much more important than the former.

Localization of brain functions: It is now generally accepted that there is a degree of modularity in aspects of brain organization. Over the years neuropsychologists and neuroscientists have accumulated some knowledge of this organization. For example, we know some brain regions are involved in processing language while other regions process visual spatial information. Finding selective involvement of these regions in complex cognitive tasks – like reasoning – can help us differentiate between competing cognitive theories that make different claims about linguistic and visuo-spatial processes in the complex task (as do mental logic and mental model theories in the case of reasoning). However, we also know that for much of the brain there is at least a one to many mapping from brain structures to cognitive processes (and probably a many to many mapping) which undercuts much of the utility of localization. Despite this caveat, localization seems to loom large in the literature.

Dissociation of brain functions: Brain lesions result in selective impairment of behavior. Such selective impairments are called dissociations. A *single* dissociation occurs when we find a case of a lesion in region *x* resulting in a deficit of function *a* but not function *b*. If we find another case, in which a lesion in region *y* results in a deficit in function *b* but not in function *a*, then we have a *double* dissociation.

The most famous example of a double dissociation comes from the domain of language. In the 1860's Paul Broca described patients with lesions to the left posterior inferior frontal lobe who had difficulties in the production of speech but were quite capable of speech comprehension. This is a case of a single dissociation. In the 1870's Carl Wernicke described two patients (with lesions to the posterior regions of the superior temporal gyrus) who had difficulty in speech comprehension, but were quite fluent in speech production. Jointly the two observations indicate a double dissociation and tell us something important about the causal independence of language production and comprehension systems. If this characterization is accurate (and there are now some questions about its accuracy) it tells us that any cognitive theory of speech production and comprehension needs to postulate two distinct functions/mechanisms.

Recurrent patterns of double dissociation provide indication of causal joints in the cognitive system invisible in uninterrupted normal behavioural measures (Shallice, 1988). Double dissociations manifest themselves as crossover interactions in neuroimaging studies. Thus, if in the case of reasoning, decision-making, and problem solving we find double dissociations along the lines of familiarity/unfamiliarity, conflict/agreement and certainty/uncertainty, cognitive theories will need to take these dissociations into consideration. Indeed, some neuropsychologists have argued that it really does not matter where the lesions are in patients (or where the activations are in neuroimaging studies), but only that there are double dissociations. While an extreme position, it is not without merit.

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Table 1: Summary of studies and areas of brain activation discussed in the chapter organized by task domain (reasoning, decision-making, and problem solving) and issues of interest (familiarity, conflict detection, and task structure).
Abbreviations: F-TL = frontal-temporal lobes, PFC = prefrontal cortex; TL = temporal lobes; VLPFC = ventral lateral prefrontal cortex; PL = parietal lobes

Domain & Studies	**Method**	**Familiarity**		**Conflict Detection**	**Task Structure**	
		Heuristic	**Formal**		**Complete Information**	**Incomplete Information**
Reasoning						
Goel et al. (2000)	fMRI	Left F-TL	PL			
Goel, Shuren, et al. (2004)	lesion	Left PFC				
Goel, Mikale & Grafman (2004)	fMRI	Left F-TL	PL			
Goel et al. (2000)	fMRI			Right PFC		
Goel and Dolan (2003)	fMRI			Right PFC		
Caramazza et al. (1976)	lesion			Right TL		
Goel et al. (2006)	lesion				Left PFC	Right PFC
Decision-Making						
De Neys & Goel (in press)	fMRI	Left F-TL				
De Neys, Vartanian & Goel (in press)	fMRI			Right PFC		
N/A						
Problem Solving						
Sirigu et al. (1995)	lesion	PFC				
Stavy et al. (2006)	fMRI			Right PFC		
Reverberi et al. (2005)	lesion			Right PFC		
Goel & Grafman (2000)	lesion					Right PFC
Channon & Crawford (1999)	lesion					PFC
Vartanian & Goel (2005)	fMRI				Left PFC	Right VLPFC

Figure Captions

1. Dissociation of systems involved in heuristic and formal reasoning processes. (A) Reasoning about familiar material (All apples are red fruit; All red fruit are nutritious; All apples are nutritious) activates a left frontal (BA 47) temporal (BA 21/22) system. (B) Reasoning about a familiar material (All A are B; All B are C; All A are C) activates bilateral parietal lobes (BA 7, 40) and dorsal prefrontal cortex (BA 6). Reproduced from (Goel et al., 2000).

¶2. The Wason Card Selection Task is perhaps the most widely used task in the cognitive literature to assess content effects in reasoning. In the original (or arbitrary) version of the task four cards are placed on a table, each having a letter on one side and a number on the other side. Two letters and two numbers are visible. The task is to determine which cards need to be turned over in order to verify the rule "if a card has a vowel on one side, then it has an even number on the other side". (The correct answer is to turn over the first and fourth cards. The first card provides confirmation for the statement while the fourth card provides evidence of disconfirmation. Information on the other two cards is irrelevant.) The basic finding is that if the task involves arbitrary material, as in the first example, performance is relatively poor (25%-30%). However, the presence of meaningful content (e.g. "if someone is drinking beer, then they are at least 21 years old"), as in the second example, dramatically improves performance (90%-95%).

3. The Rectangle and Polygon Task. In this task subjects are shown a rectangle followed by a polygon, generated by a modification to the rectangle. They are asked to compare the perimeters of the two figures and determine whether the second is larger than the first. The area of the second figure also changes with the perimeter. This change in area seems to be a salient queue for most subjects. When the perimeter changes in the same direction as the area (congruent trials) subjects perform very well on the task. However, when the perimeter does not change in the same direction as the area (incongruent trials), task performance suffers.

4. The right lateral/dorsal lateral prefrontal cortex (BA 45, 46) is activated during conflict detection. For example, in the following argument "All apples are red fruit; All red fruit are poisonous; All apples are poisonous" the correct logical answer is "valid"/"true" but the conclusion is inconsistent with our world knowledge, resulting in a belief-logic conflict. Reproduced from (Goel & Dolan, 2003).

5. The Tower of Hanoi puzzle consists of three pegs and several disks of varying size. Given a start state, in which the disks are stacked on one or more pegs, the task is to reach a goal state in which the disks are stacked in descending order on a specified peg. There are three constraints on the transformation of the start state into the goal state. (1) Only one disk may be moved at a time. (2) Any disk not

being currently moved must remain on the pegs. (3) A larger disk may not be placed on a smaller disk.

6. (a) Hypothesis generation in unconstrained anagram trials is associated with significant activation in right ventral lateral prefrontal cortex (BA 47). (b) Furthermore, activation in right ventral lateral prefrontal cortex increases as a function of decreasing constraints on the problem space in the anagram task. Reproduced from Vartanian and Goel (2005).

¶7. Double dissociation between systems for processing certain and uncertain information. *(A)* Lesion overlay maps (transverse slices, R=L), displaying left and right prefrontal cortex lesions. (B) Accuracy scores on three-term transitive reasoning. A Lesion (right prefrontal cortex, left prefrontal cortex, normal controls) by Determinacy (determinate, indeterminate) interaction shows a crossover double dissociation in the performance of left and right prefrontal cortex patients in determinate and indeterminate trials. Reproduced from (Goel et al., 2007).

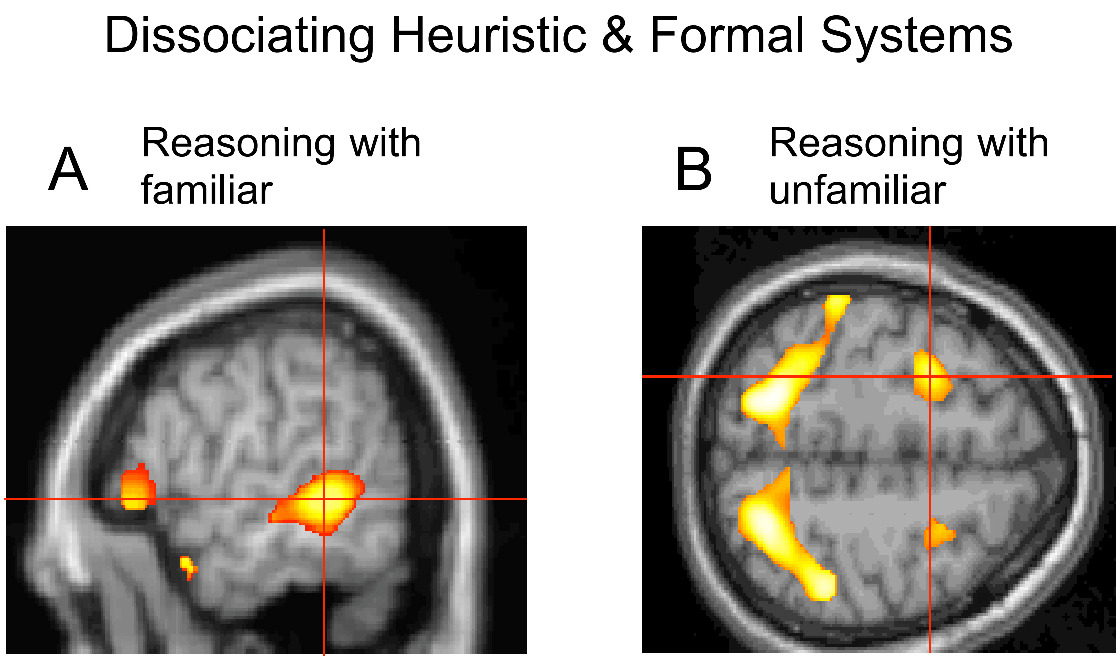
Dissociating Heuristic & Formal Systems
A
Reasoning with familiar
B
Reasoning with unfamiliar

Figure 1

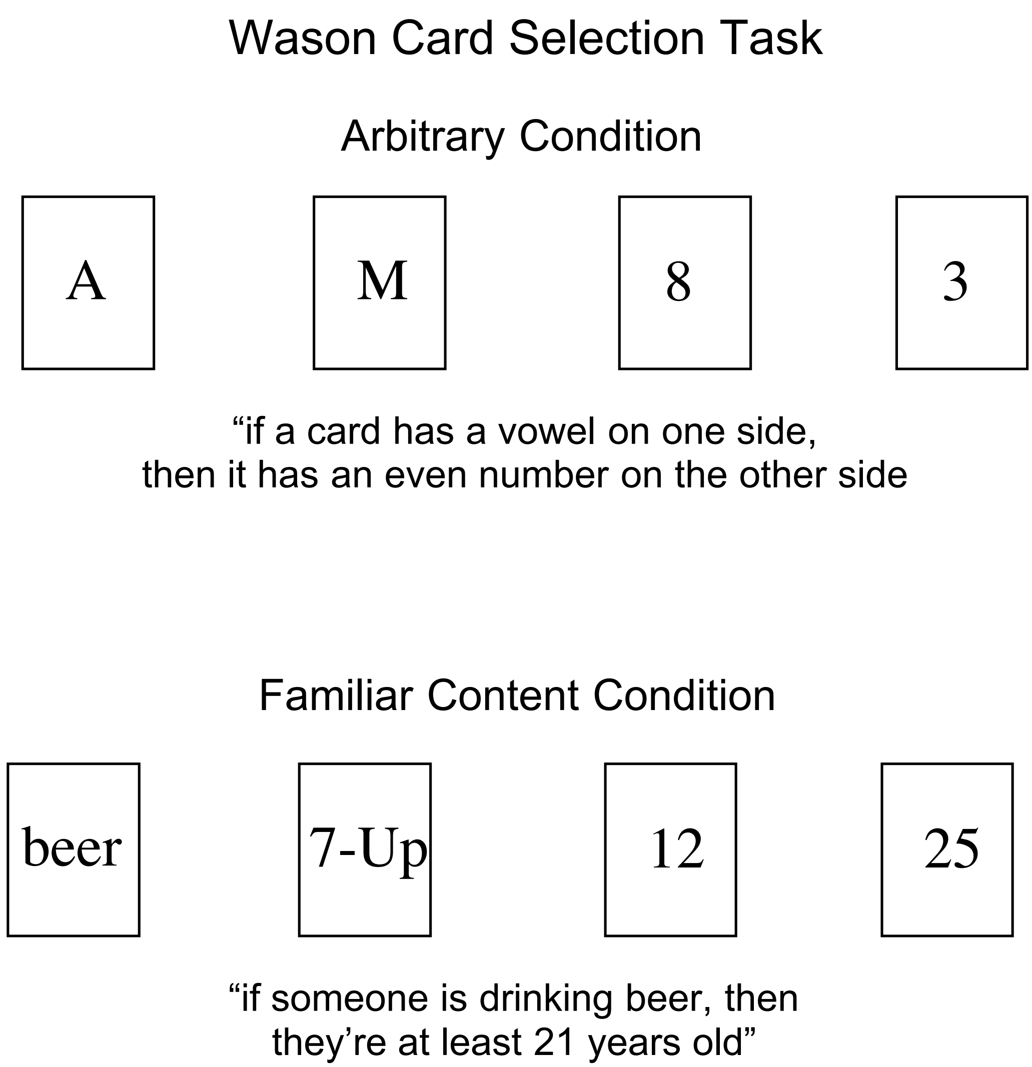
Wason Card Selection Task
Arbitrary Condition
A
M
8
3
“if a card has a vowel on one side,
then it has an even number on the other side
Familiar Content Condition
beer
7-Up
12
25
“if someone is drinking beer, then
they’re at least 21 years old”

Figure 2

Rectangle & Polygon Task

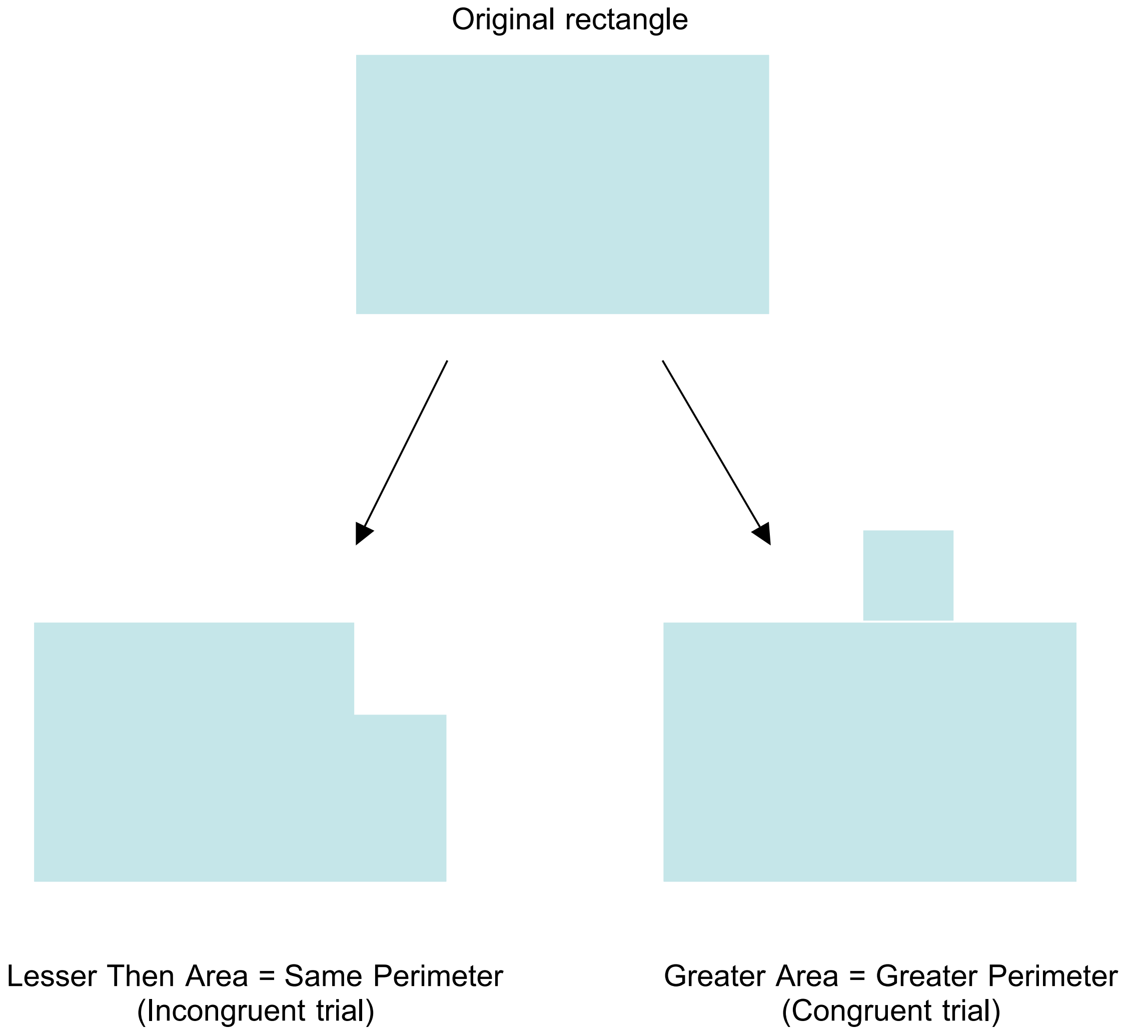

Figure 3

Conflict detection system

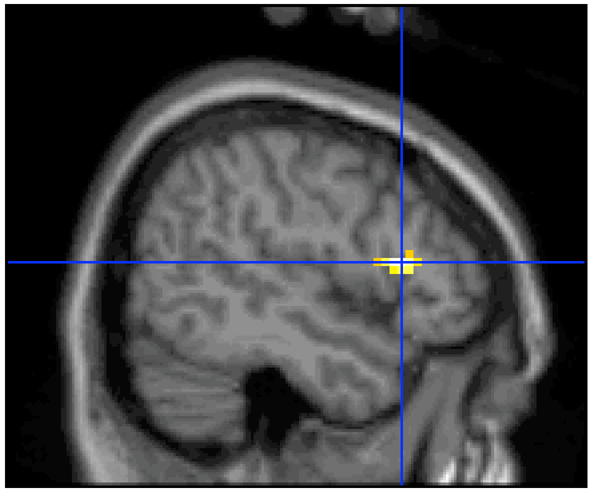

Figure 4

Tower of Hanoi Task

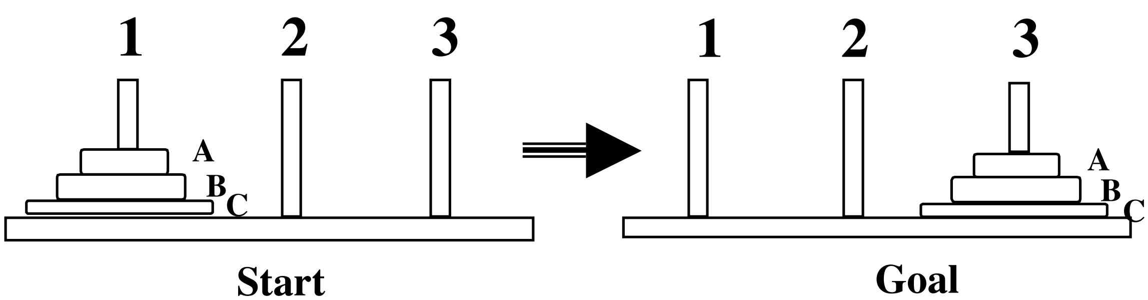

Figure 5

Right Ventral Lateral PFC is Activated by Under-Constrained Situations

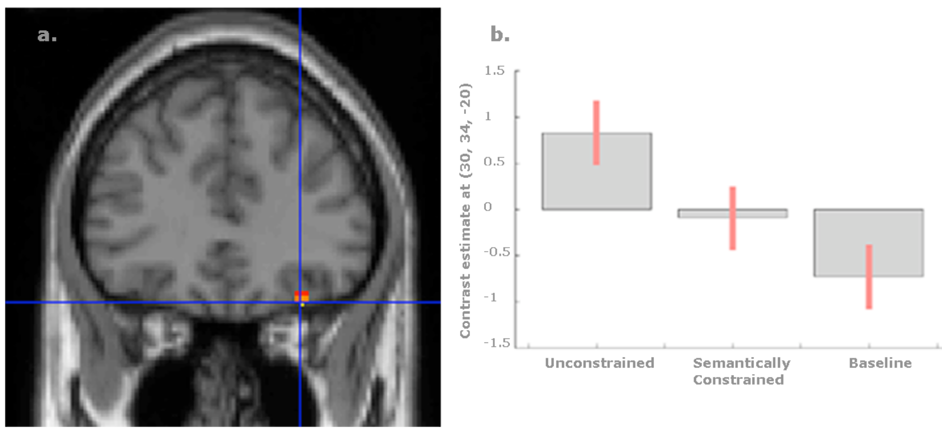

Figure 6

Dissociating Systems for Dealing with
Certain & Uncertain Information

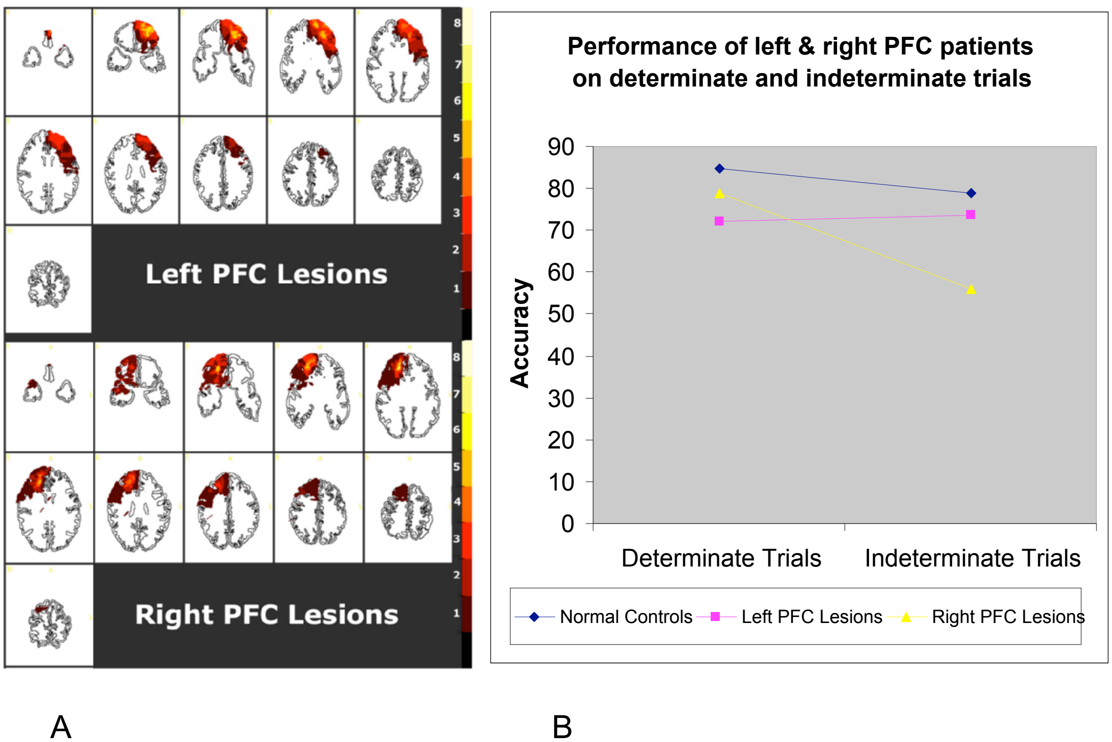

Figure 7