Focus Article

Neural basis of thinking: laboratory problems versus real-world problems

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Cognitive psychologists have long argued about the reality and significance of the distinction between well-structured and ill-structured problems. Laboratory problems are usually well-structured, whereas real-world problems have both well-structured and ill-structured components. This article shows how the neuropsychological data reinforce this distinction and suggests how this distinction may help to explain a puzzle about discontinuous performance of some neurological patients in laboratory and real-world problem situations. *WIREs Cogn Sci* 2010 1 613–621

Broadly construed, thinking is the process of manipulating mental representations to attain some goal. 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 (recursive function theory, formal logic, and probability theory, respectively). The literature on the neural basis of reasoning has recently been reviewed.[1,2] The focus of this article is on problem solving.

By the way of a definition, problem solving requires at least the following conditions: (1) there be two distinct states of affairs, (2) the agent is one state and wants to be in the other state, (3) it is not apparent to the agent how the gap between the two states is to be bridged, and (4) bridging the gap is a consciously guided multi-step process. It is only when the agent does not have at hand a single operator to bridge the gap that a problem space is instantiated to construct the sequence of operators that will effect the transformation. This definition encompasses much, but importantly not everything.

This article deals, in particular, with the research on human problem solving in both cognitive psychology and neuropsychology, and how insights from the two disciplines can be integrated to the benefit of both disciplines and advance our understanding of human problem solving.

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COGNITIVE AND NEUROPSYCHOLOGICAL FRAMEWORKS FOR STUDY PROBLEM SOLVING

The majority of the cognitive research in human-problem solving has been undertaken within the framework of information processing theory.[3] Information processing theory appeals to three main notions (Figure 1): (1) an information processing system (IPS), (2) the task environment, and (3) the problem space. An IPS is a physical symbol manipulation system with memory stores (short term, long term, and external), a processor, sensory receptors, and motor effecters. It functions under two sets of constraints. The psychological constraints consist of temporal and spatial limitations on working memory and sequential processing. (Although there are many more sophisticated accounts of psychological constraints today, these basic notions still need to be respected at some level.) The meta-theoretical constraints require that the IPS is a computational system with combinatorial syntax and semantics, and structure sensitivity to process.[4] Task environments consist of (1) the goal, (2) the problem, and (3) other relevant external factors[3]. The problem space is a computational space shaped by the interaction of the constraints inherent in the IPS and the task environment. It is defined

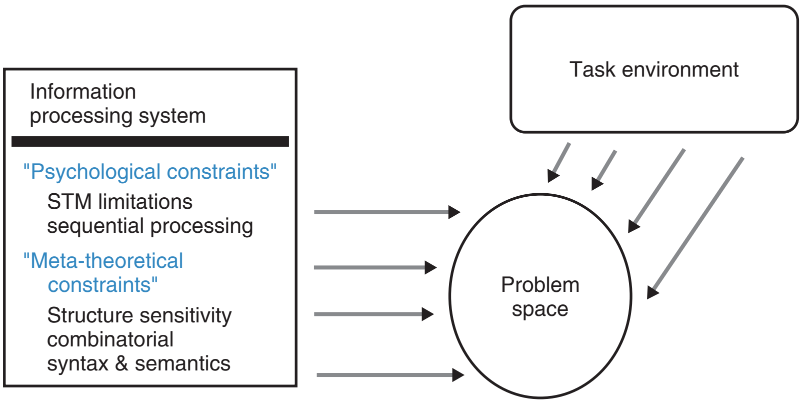

FIGURE 1 | The problem space is a computational work arena shaped by the dual constraints, of the structure of the information processing system and the structure of the task environment. It is specified in terms of state space, operators, evaluation functions, and control strategies. See Ref 3 for the classic discussion of each of these components. See Ref 4 for a particularly clear discussion of the meta-theoretical constraints. See Ref 5 for discussion of meta-theoretical constraints, structure of task environments, and their consequences for the structure of the problem space.

by a state space, operators, evaluation functions, and search strategies.

The information processing theory framework has emphasized detailed task analyses and the explicit computational characterization of the problem space. It has resulted in a number of insights into the nature of certain types of problem solving. However, 50 years after the onset of the program, the scope of the framework seems limited to a narrow range of (well-structured) problems. It is proving difficult to encompass certain critical aspects of real-world problem solving within this framework, leading some to question its scope and generality.[5] The behavioral data, however, do not convincingly resolve the impasse.

Neuropsychology has very different origins and goals than cognitive psychology. It has largely been concerned with localizing brain lesions rather than articulating cognitive processes and mechanisms. As such, it 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.[6] Some of these tasks have directly targeted complex cognitive processes. For example, card sorting tasks,[7] word similarity tasks, proverbs tasks,[8] and word definition tasks have been used to measure abstraction and generalization ability. Nonsense drawing tasks[9] and word generation tasks have been used to measure nonverbal and verbal fluency, respectively. Shell games have been used to measure rule/pattern induction.[10] Choice reaction time studies have been used to measure the use of advance information.[11] The Tower of London has been used to measure look ahead/anticipatory abilities[12] and cognitive estimation has been used to measure judgment.[13] Such tasks have come to be known as 'executive function' tasks, and presumably correspond to problem-solving tasks in the cognitive literature. (However, what aspects of thinking processes this term is meant to capture, and its relationship to the term 'problem solving' remain unclear.)

Given the focus on lesion location, neuropsychologists have primarily used very simple tasks and focused on whether patients can or cannot do a particular task. Mapping performance deficits in simple tasks to damage in specific brain regions built up a corpus of knowledge that could be used to identify lesion sites, in the absence of imaging technology. As this particular role of neuropsychology became obsolete, with the advent of modern brain imaging technologies, and as advances made by cognitive psychology in the development of computational/mechanistic theories of cognitive processes filtered across, neuropsychology shifted its focus to the understanding of brain systems in terms of cognitive mechanisms. This transition was perhaps formally marked by the publication of Tim Shallice's influential book '*From Neuropsychology to Mental Structure*',[14] in which he explicitly advocated enriching neuropsychology with theoretical frameworks and experimental paradigms from cognitive psychology. This successful endeavor has led to a hybrid discipline variously known as 'cognitive neuropsychology' or 'cognitive neuroscience', data depending loosely upon whether the focus is on patient or neuroimaging data.

The past 15–20 years of crossover fertilization between neuropsychology and cognitive psychology is beginning to alter the intellectual landscape, to the benefit of both disciplines. First, a wide range of problem-solving tasks from the cognitive literature have been introduced into the neuropsychology literature, including the standard 'well-structured' tasks,[12,15–17] mental set shift and creativity tasks,[18–22] and tasks that take the patients out of the laboratory and require them to cope with real-world situations,[23–27] among others. Second, some researchers have also focused on sophisticated task analyses and the tracing of intermittent steps between the start state and the goal state in order

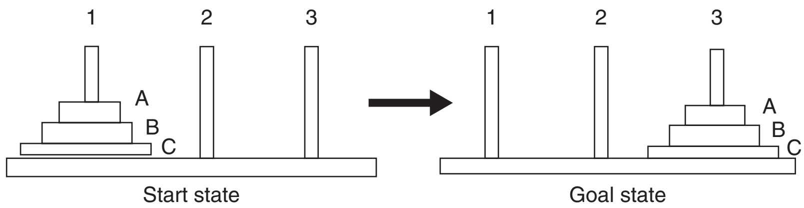

FIGURE 2 | The Tower of Hanoi Puzzle consists of three pegs and several disks of varying size. Given a start state, in which the disks are stacked on one or more pegs, the task is to reach a goal state in which the disks are stacked in descending order on a specified peg. There are three constraints 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.

to understand the impact of specific lesions on cognitive processes.[16,24,25] Third, others have tried to capture the consequences of lesion deficits in explicit computational models of the task.[28,29] Fourth, still others have tried to provide computational models of neural activity observed in specific steps of the problem-solving tasks.[30,31]

The balance of this article addresses the question as whether data generated by patient and neuroimaging studies can inform cognitive theories of problem solving and whether cognitive theories can help interpret these data. These questions encompass a great deal. To provide more than a superficial answer, I shall restrict myself to one issue that remains unresolved within the cognitive literature (i.e., that of ill-structured and well-structured problems) and a puzzle within the neuropsychology literature (i.e., the discontinuity in performance of patients with lesions to prefrontal cortex (PFC) in laboratory and real-world problem-solving tasks), and demonstrate how the neuropsychological data clarify and reinforce certain aspects of the cognitive theory of problem solving, and how cognitive theory may help to explain the neuropsychological data.

ILL-STRUCTURED AND WELL-STRUCTURED PROBLEMS

The issue of ill-structured and well-structured problems has been a point of debate and contention in the problem-solving literature for 40 years. The distinction originates with Reitman.[32] 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 in which 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.

The Tower of Hanoi, in which a set of disks are moved from one peg to another, is a typical example of a well-structured problem (Figure 2). In such puzzles the start state is completely specified, as is the goal state and the set of legal transformations (though generating or selecting the 'best' transformation at any given point may be a difficult task). Planning a meal for a guest is an example of an ill-structured task. The start state is incompletely specified (e.g., how hungry will they be? how much time and effort do I want to expend?). The goal state is also incompletely specified (e.g., how much do I care about impressing the guest? should there be three or four courses? would salmon be appropriate? would they prefer a barbecue or an indoor meal?). 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?).

Reitman's original characterization has been extended along a number of dimensions by Goel.[5] One very important—but little-noted—difference has to do with the nature of the constraints in the two cases. In the Tower of Hanoi, as in all puzzles and games, the constraints are logical or constitutive of the task. That is, if one violates a constraint or rule, one is simply not playing that game. For example, if I place a bigger disk on a smaller disk I am simply not doing the Tower of Hanoi task.

However, the constraints we encounter in real-world situations are of a very different character. Some of these constraints are nomological; many of them are social, political, economic, cultural, and so on. We will encompass the latter category under the predicate 'intentional'. In fact one can view social, cultural, and religious norms (e.g., 'Thou shalt not commit adultery. Thou shalt not lie'.) as attempts to provide structure to our lives. However, most of us quickly learn that these constraints are not definitional or constitutive. On the contrary, they are negotiable/breakable, depending on circumstances (e.g., maybe it is ok if I don't get caught).

It is also the case that in most ill-structured situations, there are no right or wrong answers, though there are certainly better and worse answers.[33] In the above dinner example, if our dinner guest eats what we serve, did we reach the correct goal state? This seems like an odd question. There will always be better and worse possibilities than any given outcome.

In well-structured problems, there are right and wrong answers, and clear ways of recognizing when they have been reached. So if I succeed in stacking my disks in descending order on peg 3 in the Tower of Hanoi task, that is the one and only possible correct answer.

All problems require registration and decomposition, or at least individuation of component parts. There are differences with respect to the lines of decomposition/individuation and the interconnectivity of components. Well-structured problems have a predetermined structure, which is either explicitly given with the problem, or is implied by the logical structure of the problem. (So, e.g., on a standard interpretation of the game of chess, each player starts with 16 game pieces. One does not have the option of claiming that the conjunction of one of the 'rooks' and 'knights' constitutes a game piece.)

In ill-structured problems, on the other hand, lines of decomposition/individuation are determined by the subject, taking into consideration the physical structure of the world, social and cultural practices, and personal preference.

In terms of the interconnectivity of parts, one finds logical interconnections in well-structured problems (e.g., in cryptarithmetic there is always the possibility that any row will sum to greater than 9 and affect the next row). Thus, the subject has no choice or selectivity in attending to interconnections. Interconnections in ill-structured problems are contingent and one has considerable latitude in determining which ones to attend and which ones to ignore.

Simon[34] has famously argued that the distinction between ill-structured and well-structured problems is ill-conceived. The so-called 'ill-structured problems' are simply structured by adding information from our background knowledge and external sources and then one can specify the problem space and search for a solution.

COGNITIVE CHARACTERIZATION OF ILL-STRUCTURED PROBLEM SOLVING

Well-structured problem solving has been extensively studied and characterized in the literature (e.g., Ref 3) Ill-structured problem solving has received much less attention. One characterization of it is offered in Ref 5. On this account, ill-structured problem solving typically involves four phases: problem scoping, preliminary solutions, refinement, and detailing of solutions. Each phase differs with respect to the type of information dealt with, the degree of commitment to generated ideas, the level of detail attended to, the number and types of transformations engaged in, the mental representations needed to support the different types of information and transformations, and the corresponding computational mechanism.[5] As one progresses from the problem scoping phases to the detailing phases, the problem becomes more structured. This is depicted in Figure 3.

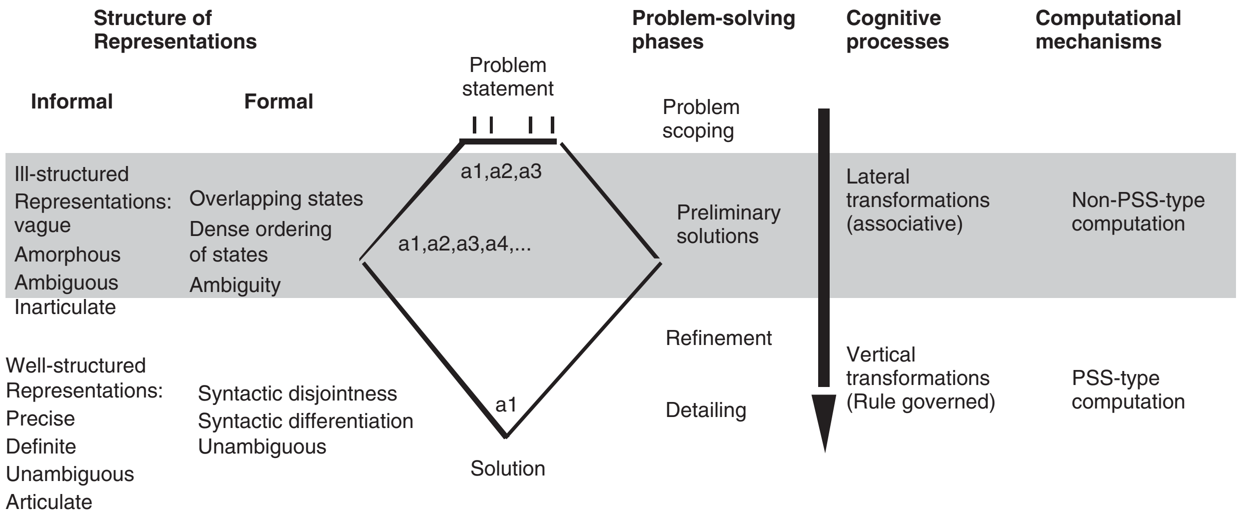

FIGURE 3 | Aspects of real-world problem solving. Unlike the state space for well-structured problems, the state space for ill-structured real-world problems must support different problem-solving phases, which need to be supported by different representational systems, cognitive processes, and computational mechanisms physical symbol systems (PSS). See Ref 5 for further discussion.

Problem scoping is the process of using personal and external knowledge to flesh out and shape, even reshape, the problem statement. Preliminary solution generation is a classical case of creative, ill-structured problem solving. It is a phase of 'cognitive way-finding', a phase of concept construction, where a few kernel ideas are generated and explored through lateral transformations. A lateral transformation is one where movement is from one idea to a slightly different idea rather than a more detailed version of the same idea. Lateral transformations are necessary for the widening of the problem space and the exploration and development of kernel ideas. This generation and exploration of ideas/concepts is facilitated by the abstract nature of information being considered, a low degree of commitment to generated ideas, the coarseness of detail, and a number of lateral transformations. The rules underlying lateral transformations are difficult to articulate.[5]

The refinement and detailing phases are more constrained and structured. They are phases where preconstructed concepts are manipulated. Commitments are made to a particular solution and propagated through the problem space. They are characterized by the concrete nature of information being considered, a high degree of commitment to generated ideas, attention to detail, and a large number of vertical transformations. A vertical transformation is one where movement is from one idea to a more detailed version of the same idea. It results in a deepening of the problem space. The rules underlying vertical transformations can often be articulated.[5]

Goel[5] has argued that the ability to engage in lateral transformations is underwritten by a mechanism that supports ill-structured mental representations and computation. Ill-structured representations are imprecise, ambiguous, fluid, indeterminate, vague, etc. The ability to engage in vertical transformations is underwritten by a mechanism that supports well-structured mental representations and computation. Well-structured representations are precise, distinct, determinate, and unambiguous. It is further argued that there is a computational dissociation between these two mechanisms.[5,35] Ill-structured and well-structured representations differ with respect to formal properties. This in turn affects the modes of inference they can participate in and the computational mechanisms required to support them.

PUZZLE OF FRONTAL LOBE PATIENT DATA

There is an interesting puzzle in the neuropsychology literature that I believe speaks to the above postulated cognitive and computational distinctions between ill-structured and well-structured problems. A subset of patients with frontal lobe lesions perform 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,[26] Eslinger and Damasio,[36] Goel and Grafman,[28] and Burgess,[37] among others.

An apt example of the patient profile under discussion is provided by Goel and Grafman's[24] patient PF. PF was an accomplished professional architect with a right prefrontal cortex (PFC) lesion. This patient scored 128 on the WAIS-R, but was simply unable to cope in the world. At the age of 56, he found himself unemployed and living at home with his mother. Because the patient was an architect, he was administered a task that required him to develop a new design for a lab space. His performance was compared with that of an age- and education-matched architect. 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 scoping phase. However, the patient's problem-solving behavior differed from the control's behavior in the following ways: (1) he had difficulty in making the transition from problem scoping to problem solving; (2) as a result preliminary planning did not start until two thirds of the way into the session; (3) the preliminary planning phase was minimal and erratic, consisting of three independently generated fragments; (4) there was no progression or lateral development of these fragments; (5) there was no carryover of abstract information into the preliminary planning or later phases; and (6) the patient did not make it to the detailing phase. This suggests that the key for 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'.[23] Channon and Crawford[23] 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 of 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 conventional 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 structured neuropsychological tests. Patients with anterior lesions were impaired in more aspects of the 'predicaments' task than the posterior patients.

EXPLAINING THE PUZZLE

A number of researchers have offered accounts to explain the puzzle. Shallice[14,38] suggests that the key issue for frontal lobe patients is 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, which is damaged in frontal lobe patients, rendering them incapable of coping with novel situations. In contrast, Grafman's[27,39] underlying intuition is that the crucial issue is patients' inability to perform in routine, over-learned situations. His structured-event complex 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. Damasio's[40] somatic markers theory focuses on patients' poor judgments in certain situations and suggests that the cause of this difficulty is the patients' inability to inform cognitive processes by visceral, noncognitive factors. Burgess[37,41,42] suggests that the critical issue for these patients is multitasking.

Goel[25,43] has argued that neuropsychological test batteries contain largely well-structured problems, whereas problems encountered in real-life situations contain both ill-structured and well-structured components. Given that different cognitive and computational mechanisms are required to deal with the two situations there may be a neuropsychological dissociation corresponding to the cognitive and computational distinctions noted above.

However, the anatomical basis of this proposed dissociation is unclear. The most important anatomical distinction within the frontal lobe literature has been between dorsolateral and ventral medial/orbital PFC. The latter is considered a part of the paralimbic system and has been implicated in emotional processing, the disturbance of which can lead to poor judgments in real-world decision making.[40,44–46] The former has been implicated in a range of cognitive functions and processes including reasoning,[1,47–50] decision making,[51] and problem solving.[18,26,30,31,52] Some recent studies are questioning this simple distinction.[53,54]

I am proposing that there is also an important hemispheric distinction in the organization of PFC which has not been fully explored. Research with split-brain patients provides considerable evidence for left hemisphere involvement (even dominance) in the critical domains of higher level thinking processes[55,56] while limiting the role of the right hemisphere, and in particular the right PFC, to little more than visual organization.[57] The first half of this conclusion has been reinforced by recent neuroimaging studies showing strong left PFC involvement in a range of cognitive processes including hypothesis generation,[58] logical reasoning,[1,59–63] inductive reasoning,[48,50] and decision making.[64]

However, the second half of this claim is much less tenable. Recent data suggest that right PFC plays a selective but critical role in situations where the problem space (1) is very broad and poorly constrained, (2) contains misleading/conflicting information, or (3) contains insufficient information to determine the conclusion. These are all hallmarks of real-world problems. For example, broadening the search space on scrambled word tasks by broadening the semantic categories words can belong to (e.g., make the word 'knife' with IKFEN; make a word for a kitchen utensil with IKFEN; make a word with IKFEN) reduces task constraints and selectively engages right PFC.[65] Hypothesis generation tasks, such as the Matchstick problems, that involve mental set shifts (lateral transformations) to overcome implicit misleading cues selectively activate right PFC in the misleading condition.[18,50] Even in a classic 'left hemisphere' task such as logical reasoning, a recent study suggests a double dissociation such that patients with left PFC lesions are 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), whereas patients with right PFC lesions were selectively impaired in trials with incomplete information (i.e., indeterminate trials; A>B, A>C, B>C).[66,67]

The overall pattern of these data leads me to speculate that the inarticulate, ill-structured representational system may be underwritten by the right PFC, whereas the articulate, well-structured representational system may be underwritten by the left PFC.

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 PFC may be necessary and sufficient for task solution. However, in cases where the start state pattern obstructs/hinders or totally underspecifies a solution path through the problem space, the left hemisphere interpreter may prematurely lock onto erroneous solutions. In such situations, the right PFC 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.[5]

Many of the patients with the neuropsychological profile under consideration have lesions to right PFC.[37] The solution to the puzzle of frontal lobe patients who perform well in the laboratory but stumble when encountering (even simple) real-world situations may be that these lesions impair their ability to maintain and transform ill-structured representations. As standard neuropsychological test batteries consist only of well-structured problems, while real-world problems have both ill-structured and well-structured components (the former preceding the latter), patients may perform well in the lab but stumble in the real world.

If this is a genuine double dissociation (and if success in the world consists of primarily dealing with the lack of structure), it should be possible to find individuals exhibiting the reverse pattern: i.e., being very successful in the world but underperforming in the neuropsychology laboratory. The problem here is that if someone is successful in the world, there is very little reason for them to be tested in the neuropsychology laboratory. Certainly, there are anecdotal stories of individuals who have amassed great power and wealth but would turn in a mediocre performance on IQ tests. (In these cases, we would simply say ‘so much the worse for IQ tests!’).

The fact that there is a neuropsychological dissociation corresponding to the cognitive and computational distinctions between ill-structured and well-structured problem-solving reinforces these distinctions at the cognitive level and suggests that they engage different neuronal systems. As most real-world problem situations have both ill-structured and well-structured components, we will only understand the underlying processes if we are prepared to recognize the limits of information processing theory systems and postulate additional mechanisms and look at how the two might interact to mediate our successful functioning in the real world.

CONCLUSION

The article began by posing the question whether neuropsychological data and cognitive theories of problem solving can usefully inform each other. It has been argued that neuropsychology data can speak to at least one crucial issue in the problem-solving literature: the reality of the distinction between ill-structured and well-structured problems. Unsurprisingly, the conversation goes both ways. Although the neuropsychology data reinforce the postulated cognitive and computational dissociations, the cognitive and computational distinctions help explain the neuropsychological data. We will undoubtedly find other similar convergences that will help to further enrich our theories of human problem solving.

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