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EXECUTIVE CONTROL OF SCIENTIFIC DISCOVERY

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1. Introduction

Within cognitive science, contrasting models of scientific discovery are advocated. On the one hand, scientific discovery is often conceived as a demanding enterprise involving considerable conscious mental resources. For example, Tweney (1988) and Gooding (1990) have demonstrated that the cognitive processes employed by scientists such as Faraday during major discoveries involved a highly organized and deliberate process of scientific work aimed towards some definite goal. In addition, many computational models, such as BACON (Langley, Simon, Bradshaw, and Zytkow, 1987), view scientific discovery as a heuristically-driven process. On the other hand, many scholars assume scientific discovery is often produced by cognitive processes over which we have little control or awareness. Wallas (1926) proposed that creative discoveries are produced by incubation, that is, the unconscious attempt to solve a problem while engaging in other activities. In the chance-configuration theory of scientific creativity, Simonton (1988) argues that conceptual combination of ideas is 'blind' to possible outcomes. In this paper, I will outline a comprehensive framework that can account for both the effortless and controlled processes of scientific discovery.

To appreciate how these contrasting conceptualizations can be explained, let me outline the key attributes of scientific discovery that provide the central explanatory goal of this framework. Scientific discovery is a complex activity. Each activity can be broken down into a number of specific sub-processes. Some activities can be conducted relatively effortlessly. For example, a standard laboratory procedure may be executed without considerable mental effort. Other activities (e.g., explaining an anomalous finding) demand considerable mental resources. Moreover, these activities require elaborate and diverse (e.g., schema and mental imagery) mental representations. Additionally, scientists have numerous reasoning strategies and heuristics to generate and evaluate these representations. Most models of scientific discovery have focused on the types of mental representation (e.g., mental models and neural network) as well as the reasoning strategies that operate on these mental representations. While this research program is important, it neglects the mechanisms determining when and why particular representations and reasoning strategies are utilized. In this paper, it will be argued that scientific discovery depends on the coordination of mental representations and reasoning strategies by the executive control system. If our goal is to develop a comprehensive model of scientific discovery that explains the actual practice of scientists, an analysis of the control processes is essential for understanding the actual practice of scientists as they engage in scientific discovery. Although I wish to extend the model discussed below to the psychological processes employed by actual scientists engaged in the process of scientific discovery, my immediate goal is to explain the psychological processes involved in laboratory rule-discovery tasks.

Within psychology, the discovery process is typically examined with a variety of laboratory tasks. Use of laboratory tasks is dependent on the widely-held assumption that the same psychological processes employed in laboratory tasks are employed by practicing scientists (Gholson, Freedman, and Houts, 1989; Neimeyer, Shadish, Freedman, Houts, and Gholson, 1989). Typically, these tasks involve asking participants to discover some target hypothesis. In Wason's (1960) 2-4-6 task, people attempt to discover a target hypothesis (e.g., increasing numbers) for which the sequence, 2-4-6, is one of many instances. Subjects generate experiments to test their hypotheses and the experimenter informs the participants whether the sequence is an instance of the target hypothesis. As a rule, subjects generate tests that are instances of their current hypothesis. For example, participants initially test hypotheses, such as, 'even numbers increasing by twos,' by proposing sequences such as 6-8-10 and 10-12-14. Furthermore, subjects rarely generate tests that are not instances of their hypotheses (e.g., 1-3-5 to test the hypothesis, 'even numbers'). Even when people are instructed to try to disprove their hypotheses, they often do not benefit from this information. Finally, encouraging consideration of competing hypotheses has produced evidence is mixed (see

Freedman, 1992a, 1995, for review).

As I previously argued (Freedman, 1995, 1998), encouraging the generation and evaluation of alternative hypotheses does not always improve performance because people have not had to explicitly state alternative hypotheses. When subjects do not have to state their hypotheses explicitly (Tweney, Doherty, Worner, Pliske, Mynatt, Gross, and Arkkelin, 1980), they have difficulty keep track of more than one hypothesis simultaneously. In a series of studies (Freedman, 1992a, 1992b; Freedman and Endicott, 1997), I have compared participants who have to state a single hypothesis on each trial to those participants who state two hypotheses on each trial. Several consistent findings emerge. First, although testing multiple hypotheses does not always increase the likelihood that individuals will discover the target hypothesis, it decreases the number of experiments conducted. Second, testing multiple hypotheses increases the likelihood that the tests conducted are not instances of the current hypothesis. Third, the presence of multiple hypotheses increases the amount of disconfirmation received. Thus, multiple hypotheses lead to the efficient elimination of incorrect hypotheses.

Several explanations have been offered to account for these findings. Wason argued that people are biased toward seeking conformation and reasoners fail to appreciate the importance of falsification. However, Klayman and Ha (1987) have pointed out that experiments intended to confirm one's focal hypothesis may produce disconfirmation depending on the feedback. When an individual generates the sequence, 100-200-300, to test the hypothesis, "multiples of ten," being informed that the sequence is not an instance of the target hypothesis would disconfirm this hypothesis. Klayman and Ha labeled positive tests those instances of a current hypothesis. Negative tests are experiments that are not instances of a current hypothesis. Klayman and Ha suggest that people rely on positive tests. Several authors (Baron, Beattie, and Hershey, 1988; Farris and Revlin, 1989; Freedman, 1995, 1998; Sanbonmatsu et al., 1998) have proposed that reliance on positive tests and the inability to benefit from disconfirmation may be attributable, in part, to a failure to consider alternative hypotheses. However, these explanations merely redescribe the behavior of the participants in these studies. Consequently, it is necessary to explain the cognitive processes that underlie the reliance on positive tests and a single hypothesis. Klahr and Dunbar (1987) have suggested that scientific discovery involves a search through two problem spaces:

a hypothesis space and an experiment space. The hypothesis space is the universe of all possible hypotheses within a particular domain and the experiment space is the universe of all possible experiments within that domain. Furthermore, Freedman (1995, 1998) and Mynatt, Doherty, and Dragen (1993) have argued that working memory (WM) constrains the ability to consider multiple hypotheses (MH).

Before spelling out how WM influences scientific discovery, it is necessary to describe this system. Working memory reflects the temporary activation of knowledge. Working memory is a mental workspace where information can be manipulated. Baddeley (1986) holds that WM can be divided into three major subsystems: articulatory-rehearsal loop, visuo-spatial sketchpad and executive-control system. The articulatory-rehearsal loop and visuo-spatial sketchpad are responsible for the storage and maintenance of verbal and visual information. These storage systems are supervised by the executive-control system. Although the executive-control system plays a central role in human thought, several authors (Baddeley, 1996; Monsell, 1996) have commented that the precise mechanisms of executive control are poorly understood. The executive-control system allocates mental resources to the storage subsystems, determines whether information should be encoded into memory, selects and executes various strategies, inhibits behavior after goal satisfaction or when a new goal is activated, and monitors and evaluates one's performance. Similarly, Robin and Holyoak (1995) have suggested that the executive-control system is responsible for the construction, maintenance, and manipulation of mental representations towards goal achievement. The coordination of various goals is supervised by the executive-control system (Jonides, 1995). Furthermore, the generation and maintenance of multiple goals while performing other mental computations demands processing capacity (Just, Carpenter, and Hemphill, 1996).

Unless one is willing to assume that a homunculus directs strategy selection, a system of goal coordination and strategy selection that does not require some conscious mental agent is needed. Within SOAR (Newell, Rosenbloom, and Laird, 1989), strategy selection is accomplished via a two-stage process. During elaboration, activation spreads in parallel from a goal to the associated strategies. The decision stage selects the strategy that maximizes goal satisfaction. Strategy selection is also determined by the strategy's current strength and level of activation. The strength is determined by the strategy's prior success. The more successful a strategy is, the greater the future likelihood of selecting that strategy. The current level of activation is determined by the recent history of a particular strategy. For instance, even though people may not normally select negative tests, the likelihood of generating a negative test may increase when it has been used previously. Finally, strategy selection is determined by intrinsic factors (e.g., baseline strength, prior knowledge) and extrinsic factors (e.g., task instructions). Additionally, the generation of new goals may often be defined from the information received from the environment (e.g., receiving disconfirmation). Thus, the automatic spread of activation to hypotheses and strategies explains how hypotheses are generated and strategies selected without positing a homunculus.

Working memory may constrain the ability to consider MH for one of two reasons. First, reasoners may lack storage capacity. Indeed, Mynatt, Doherty, and Dragen have argued that reasoners can only store one hypothesis in WM at a time. Clearly, people must maintain hypotheses in working memory. However, generating and evaluating hypotheses involve much more than merely retaining hypotheses. Rather, it involves coordinating various activities including hypothesis generation, strategy selection, data interpretation, and hypothesis revision. Unlike Mynatt et al., Freedman (1998) argued that scientific discovery is constrained by the executive-control system's allocation of mental resources to various activities needed to achieve a scientist's goals. Although this paper will focus on the control functions of the executive-control system, it is assumed that the storage and control processes are separate but interacting constraints on scientific discovery. As additional WM capacity is required to store hypotheses, resources are drained from the executive-control system. Likewise, as executive-control system is needed to supervise the scientific discovery process, less capacity is available for storage. In their 3CAPS model of language comprehension, Just, Carpenter, and Hemphill (1996) specify that as the storage capacity of WM begins to reach its maximum level, the number of processing cycles needed to accomplish some activity (e.g., problem solving) increases.

2. Executive Control of Scientific Discovery

With this background, the role of executive-control processes during scientific discovery can be articulated. Within this framework, scientific discovery is conceptualized as a goal-driven process (Gholson, Freedman, and Houts, 1989). The primary goal is to produce the best theory or explanation of a particular phenomenon or body of evidence. However, numerous subgoals are embedded with this primary goal. Specifically, scientists select various strategies to achieve their goals. A strategy is any plan, heuristic, algorithm, or procedure used to achieve goals. Whenever a goal is satisfied or a new goal is elicited, the executive-control system is activated. The executive-control system attempts to minimize the costs of strategy selection by choosing a strategy that can be executed automatically. Once a strategy, capable or automatic execution, is activated, it continues to completion unless an error is detected or a new goal is activated. However, when the importance of a particular goal is sufficiently high, a scientist may override the automatically-executable strategy in favor of a demanding strategy that is perceived to increase the chances of goal satisfaction. Therefore, a central task for the executive-control system is to select among competing strategies (Logan, 1985). The executive-control system directs scientific discovery iteratively through three phases: hypothesis generation, hypothesis evaluation, and a hypothesis revision. Extending the framework developed by Klahr and Dunbar (1988), Freedman (1992a, 1995) suggested that this process is embedded within a search through three problem spaces: a hypothesis space, experiment space, and a goal or strategy space (see Figure 1). The goal or strategy space is the set of heuristics that direct the search through the experiment and hypothesis spaces. The executive-control system determines whether additional mental resources are need during to search through these problem spaces. Finally, the strategies discussed in this paper do not exhaust the strategies employed in either Wason's 2-4-6 task or scientific discovery. This discussion is meant to illustrate the ways in which the executive-control system coordinates the selection and execution of strategies towards the goal of scientific discovery.

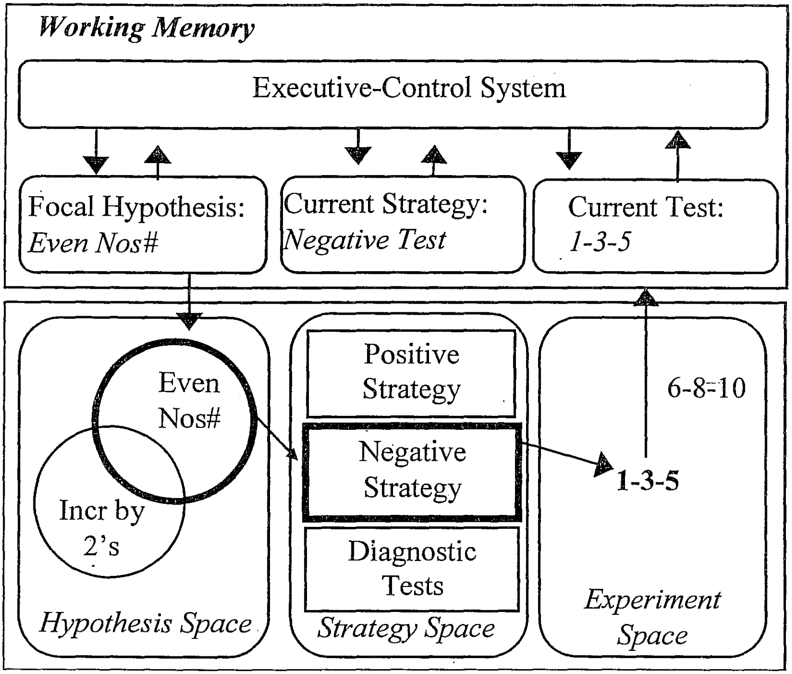

FIGURE 1: Executive control of the search through the hypothesis, experiment, and strategy space (adapted from Freedman, 1998).

3. Hypothesis Generation Stage

When faced with evidence to be explained or a problem to be solved, the executive-control system sets as its current goal the creation of a likely hypothesis. A variety of hypothesis-generation strategies are available. Among scientists, analogies are often used to generate new hypotheses (Klahr, 1996; Thagard, 1992). During hypothesis generation, activation spreads from the available evidence to the associated hypotheses. Like RED (Josephson and Josephson, 1994), as each hypothesis is activated, the executive-control system assigns it a level of confidence or plausibility. The plausibility is determined by a variety of factors including the degree of activation, the extent to which the hypothesis accounts for the available data, and the number of hypotheses accessed. When generating hypotheses, a scientist must also decide when to terminate the generation task. As part of its supervisory functions, the executive-control system controls the termination of hypothesis-generation process. Because a highly plausible hypothesis is initially generated, hypothesis generation often terminates after the first hypothesis is activated. Therefore, MH are not generated without an explicit goal because searching for additional hypotheses requires controlled information processing.

Generating hypotheses reflects constructing, and modifying mental representations within working memory. Only hypotheses, which are active in WM, will be evaluated. The complexity of a hypothesis determines the storage capacity needed. Indeed, the preference for simplicity in scientific theories may be due to the fact that simple hypotheses occupy less working memory. However, the storage demands of hypotheses can be reduced in several ways. First, consistent with the conceptualization of long-term working memory (Ericsson and Kintsch, 1995), individuals may be able to encode their hypotheses, in familiar domains, into memory in a highly accessible format. Indeed, because scientists work with well-known theories, they may be able to reduce the WM load of considering competing theories by retaining these theories in long-term working memory. Second, Schunn and Klahr (1995) have suggested that hypothesis formation often may involve a piecemeal process. Due to WM limitations, the complexity of scientific theories may necessitate that scientists consider part of their theories or part of the available evidence. Klahr (1996) has found that, on scientific discovery tasks, both children and adults often focus on one dimension of their hypothesis or evidence. Third, people can form an external representation of their hypotheses. For example, scientists may keep notebooks to record the develpment of their theories. As Freedman (1995) suggested, by forcing my subjects to state alternative hypotheses on a response sheet, they provide an external memory aid that reduces the WM load. All of these options are controlled by the executive control system.

When participants are required to propose multiple hypotheses, the executive-control system switches goals. Similarly, Klahr (1996) has suggested that the consideration of MH depend on the individual's goals. Additionally, Freedman (1995) argued that asking individuals to consider multiple hypotheses may result in a more extensive search of the hypothesis space. Indeed, Klahr, Dunbar, and Fay (1990) found that MH were effective when they came from different parts of the hypothesis space.

Freedman (1992a) found that multiple hypotheses increased the number of unique hypotheses generated. Within the present framework, the search of the hypothesis space is directed by the executive-control system.

4. Hypothesis Evaluation Stage

Once one or more hypotheses are generated, the next goal is to select a hypothesis-evaluation strategy. Numerous strategies exist to determine the validity of a hypothesis. The number and types of hypotheses will influence the type of strategy selected. Once a strategy is selected to test a specific hypothesis, activation spreads from the hypothesis through strategy space into the experiment space (see Figure 1). Activation spreads as a function of the association between the hypothesis and the experiment. The most strongly activated experiment will be selected to test the focal hypothesis. This process may explain why people tend to select prototypical instances of a focal hypothesis. When evaluating a single hypothesis (SH), people typically select positive tests because extensive experience has made it the strongest strategy capable of automatic execution. Oaksford, Morris, Grainger, and Williams (1996) found that draining the executive-control system's resources increases the likelihood of choosing confirmatory tests on Wason's selection task. Additionally, when testing a SH, positive tests are selected because the executive-control system activates a goal of obtaining evidence to support a current hypothesis. Specifically, people attempt to determine what evidence is sufficient to account for the focal hypothesis (Klayman and Ha, 1987). Unless individuals are given an explicit goal (e.g., task instructions), people do not generate tests negative tests because these tests require additional WM resources.

The presence of alternative hypotheses reduces the reliance on positive tests (Baron, Beattie, and Hershey, 1988; Freedman, 1992a; Freedman and Endicott, 1997). Freedman (1998) proposed that MH increase the use of strategies (i.e., negative tests, diagnostic tests) leading to disconfirmation (Freedman, 1992a, 1992b; Freedman and Endicott, 1997; Klahr and Dunbar, 1987) because MH may increase the consideration of a hypothesis' necessity. Specifically, the executive-control system shifts goals from seeking evidence to support the focal hypothesis to determining which of the alternative hypotheses is incorrect. Additionally, Freedman (1995) suggested that MH might suggest where in the experiment space disconfirmation might be obtained. When testing MH, the only way to guarantee one hypothesis will be disconfirmed is to conduct a diagnostic experiment. A diagnostic experiment is a sequence that is a positive test of one hypothesis and a negative test of the other hypothesis. Successful rule discovery has been associated with the use of diagnostic experiments (Freedman, 1992a; Freedman and Endicott, 1997). Because MH facilitate the elimination of incorrect hypotheses, MH participants often discover the target hypothesis with less experimentation than subjects testing a SH (Freedman, 1992a, 1992b; Freedman and Endicott, 1997).

Once the results of a particular experiment are received, the status of the current hypotheses must be determined. When hypotheses are confirmed, little WM resources are needed to deal with this information. When feedback is dichotomous, as is the case in the 2-4-6 task, decisions about the status of the current hypothesis are relatively unambiguous. However, because the results of experiments are typically complex, data interpretation is often cognitively demanding. As Klahr (1996) notes, evidence evaluation involves several specific processes including, determining what features of the data are relevant, evaluating and reducing the noise in the data, and comparing the representation of the data to the hypotheses currently active in working memory. Given this, it is not surprising that Freedman and Smith (1996) found that people's prior theories did not influence their perception of scatterplots unless individuals received an explicit goal to consider their prior theories.

5. Hypothesis Revision Stage

When a hypothesis is eliminated, the executive-control system activates a goal of seeking a new hypothesis. Anomalies play a crucial role in scientific discovery because they provide the basis for conceptual change (Darden, 1992; Nersessian, 1992; Gooding, 1992). A variety of strategies exists for revising hypotheses (Klahr, 1996) and responding to anomalous data (Chinn and Brewer, 1992). Chinn and Brewer (1992) have suggested that when facing anomalous or disconfirmatory evidence, individuals can ignore the anomalous data, hold it in abeyance, or revise their theory. As Tweney (1989) notes, Faraday ignored disconfirmatory evidence during the discovery of electromagnetic induction. Likewise, Mitroff (1974) found that scientists advocating competing theories of lunar geology were able to reject evidence that apparently disproved their theories. In simulating the latent learning controversy, Freedman (1992c) found that when the weight of disconfirmatory evidence was reduced, the competing representations could be formed. Within the current framework, the executive-control system may modify the evidence's significance when the evidence does allow the individual to achieve their goals or when the effort needed to integrate the evidence is greater than the resources the individual is willing to dedicate. While Gorman and his colleagues (Gorman, 1986; Gorman and Gorman, 1984) found that encouraging the generation of negative tests increased the likelihood that participants discovered the target hypothesis, others studies (Gorman, Stafford, and Gorman, 1987; Tweney et al., 1980) have shown that encouraging individuals to seek disconfirmation does not increase the likelihood that they will discover the target hypothesis. Thus, both scientists and non-scientists have considerable difficulty dealing with evidence that can not be clarified by a current explanation. As Freedman (1998) suggested, hypothesis revision only occurs for those hypotheses currently active in working memory. To make an appropriate revision of a hypothesis, the executive-control system must recognize that a current hypothesis has been disconfirmed. Next, the goal of seeking a new hypothesis must be activated. To generate a new hypothesis, the previous evidence must be searched to determine plausible new hypotheses. Finally, the new hypothesis must be stored in WM. The considerable WM resources needed to accomplish these tasks may hinder hypothesis revision. Multiple hypotheses may reduce the mental resources necessary to utilize disconfirmatory information because an alternative hypothesis is already active within WM. Indeed, Darden (1992) has suggested that during scientific discovery, the generation of MH is necessary for anomaly resolution.

6. New Avenues for Research

Besides explaining prior psychological research, viewing scientific discovery from the perspective of the executive-control system provides original avenues for research. First, because the executive-control system governs strategy selection, variability among individuals' performance may be attributable to strategic differences. Specifically, additional WM may increase the likelihood that individuals may select more resource-demanding strategies. Freedman and Endicott (1997) grouped individuals into high and low WM groups based on a progressive-matrices test that measures the ability to maintain multiple goals in WM (Just, Carpenter, and Hemphill, 1996). High and low WM individuals participated in Wason's 2-4-6 task. Individuals with high WM were more likely to discover the target hypothesis because high WM individuals generated more negative tests, received more disconfirmation and generated more diagnostic tests. The difference in the type of experiments conducted suggests that individual differences in WM produce changes in the selected strategies.

Second, the proposed framework assumes additional mental resources are required whenever the executive-control system is invoked, the time necessary to evaluate hypotheses should be affected the number of hypotheses and the number of hypothesis revisions. Since previous research relies on summary statistics, such as likelihood of discovering the target hypothesis or the number of positive tests, a detailed specification of the component cognitive processes is not possible. Consequently, we need an explanation of the underlying cognitive processes as well as we need precise measures of hypothesis testing while people engage in scientific discovery. With Britton, Woodruff, and Vernagus, I (Freedman, Britton, Woodruff, and Vernagus 1998) have begun to investigate the process of on-line discovery. Specifically we were interested in the role of the number of hypotheses and the number of hypothesis changes on on-line hypothesis evaluation. In this study, high and low WM participants were shown either one or two initial hypotheses and a number sequence that is an instance of the provided hypotheses. Subjects were told that the number sequence (e.g., 2-4-6) was one of many instances of a target (e.g., even numbers). The initial sequence was followed six additional number sequences that are instances of a target hypothesis. Each sequence was presented for three seconds. Some sequences (e.g., 20, 24, 28) were consistent with the initial rules (e.g., increasing by fours) while other sequences (e.g., 1, 5, 6) were inconsistent. The randomly-placed inconsistent sequences forced subjects to change their hypotheses. Because evidence was presented for a fixed duration, hypothesis revision was determined by the efficiency of the executive-control system. On a particular trial, the evidence resulted in two, one, or no changes in the original hypotheses. Participants used each sequence to evaluate the initial hypotheses and to generate a new hypothesis to replace a disconfirmed hypothesis. After the six sequences had been presented, they then were shown two hypotheses and decided which hypothesis accounted for the previous sequences. The time subjects took to decide which hypothesis was correct as well as their accuracy was recorded.

As can be seen in Figure 2, overall, the time to decide which hypothesis was correct increased as the number of hypothesis changes increased. Furthermore the high WM individuals were faster than low WM individuals. As the hypothesis changes increased, low WM individuals exhibited a relatively greater increase in reaction times than high WM individuals. Examining the percent of correct hypotheses selected, several findings can be observed (see Figure 3). First, high WM individuals were also more accurate than low WM individuals. In addition, as the number of hypothesis changes increased, the accuracy decreased. As the hypothesis changes increased, low WM individuals exhibited a relatively greater decrease in accuracy than high WM individuals. More importantly, Figure 4 shows that hypothesis change had a relatively greater impact on reaction times in the SH condition than in the MH condition. The presence of an alternative hypothesis in WM meant that participants did not have to generate a new hypothesis when an initial hypothesis is eliminated. Instead, they simply could switch to the alternative hypothesis. In summary, as the number of hypothesis changes increased, reaction times increased and accuracy decreased because the executive-control system dedicates it resources to the process of hypothesis revision. High WM individuals have an advantage because they can effectively monitor the incoming evidence and engage in hypothesis revision when necessary. Thus, the present study supports the role of the executive-control system during hypothesis evaluation.

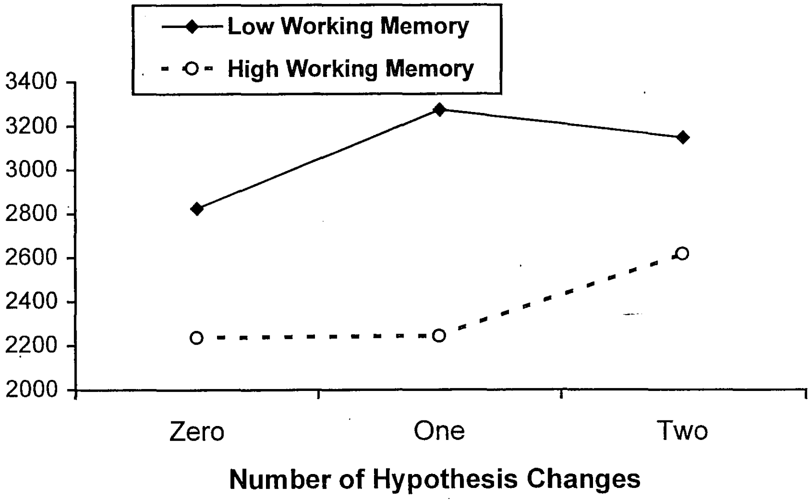

FIGURE 2: Mean reaction time as a function of individual differences in working memory and number of hypothesis changes (Freedman, Britton, Woodruff, and Vernagus, 1998).

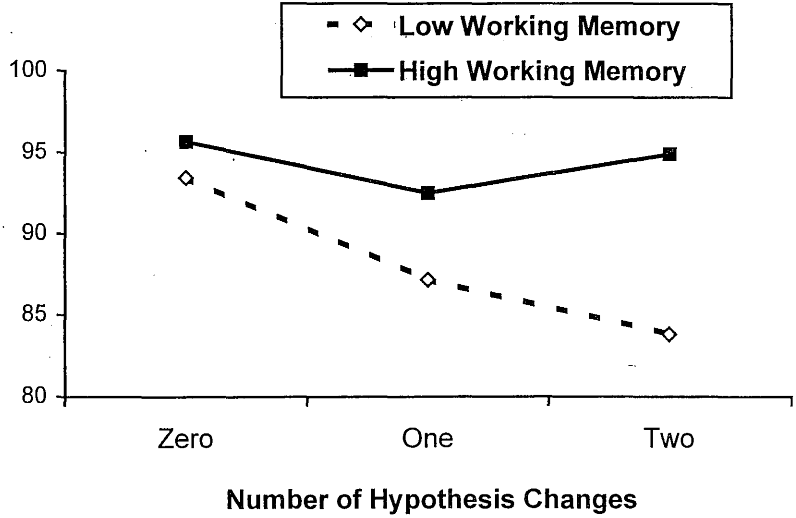

FIGURE 3. Mean accuracy as a function of individual differences in working memory and number of hypothesis changes (Freedman, Britton, Woodruff, and Vernagus, 1998).

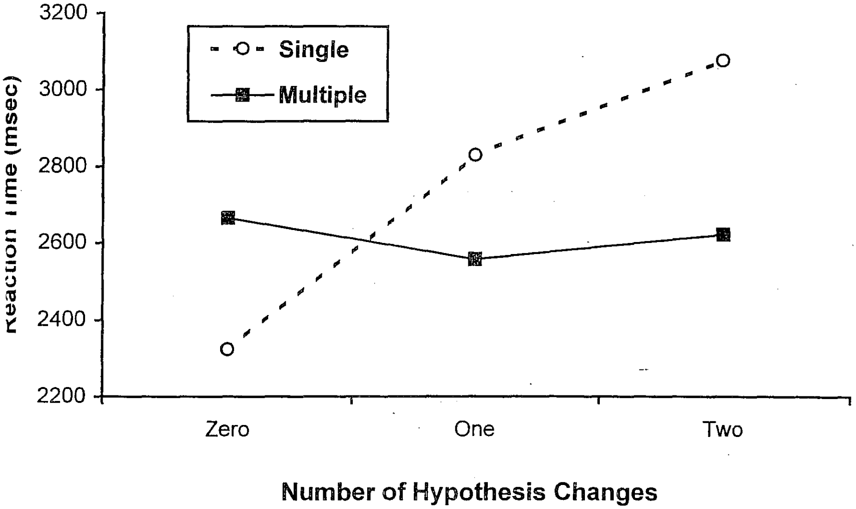

FIGURE 4. Mean reaction time as a function of number of hypotheses and number of hypothesis changes (Freedman, Britton, Woodruff, and Vernagus, 1998).

7. Implications for Models of Scientific Discovery

This framework has numerous implications for model-based approaches to scientific discovery. This framework reconceptualizes scientific discovery in terms of the control processes that operate upon scientists' representations and strategies. Specifically, scientific discovery is viewed as a highly goal-directed process. The scientist's goals determine which representations and strategies are activated. The coordination of goals and subgoal management is supervised by the executive-control system. Because the executive-control system initiates processes that can be executive automatically as well as directing those activities that require considerable mental resources, the proposed framework provides a comprehensive account of scientific discovery. Second, this framework reconceptualizes the definition of scientific thinking. Scientific thinking is often defined in terms of either the use of particular mental representations or the manipulation of mental representations with various strategies or heuristics. Within the present framework, the operation of executive-control system alone is not sufficient for defining scientific thinking, but the executive-control system must be bound to specific representations and strategies. However, it is the executive-control system that provides the inferential work necessary for scientific discovery.

Viewing scientific discovery as being managed by the executive-control system is relevant to the philosophy of science. Specifically, the present framework provides a fresh perspective on the rationality of the discovery process. Evans and Over (1996) have suggested two definitions of rationality. Rationality$_1$ assumes that reasoning is rational to the extent that it permits individuals to achieve their goals. According to Rationality$_2$, people are considered irrational to the extent that behavior deviates from the standards of normative theory. Because individuals may have the goal of discovering the target hypothesis while minimizing WM resources, generating a positive test of a single hypothesis, by Rationality$_1$, may be considered rational. Furthermore, testing a single hypothesis often leads to the correct solution. However, in view of the fact that the selection of positive tests and single hypotheses decrease the likelihood of discovering target hypothesis, these strategies could be consider irrational. Unlike Wason who believed that scientific reasoning is inevitably irrational, this framework does not view the reliance on positive tests and the neglect of negative tests as inherently irrational. Instead, like other cognitive models (Simon, 1955), deviations from rational thought are the result of information-processing limitations and the individual's goals. Unlike other models, higher levels of rational thought are within the reach of people's information-processing capabilities when testing MH because the executive control system shifts goals. Within this framework, the central constraint on rational thought is the ability of the executive-control system to select the appropriate goals and representations. Therefore, unlike Evans and Over, goal achievement is not the primary issue, rather, the appropriateness of the goals may determine whether reasoning is rational. Goal appropriateness refers to the degree to which an agent's activities are consistent with the situation. To generate an appropriate goal, an agent must form the correct problem representation. Furthermore, the presence of MH results in the executive-control system eliciting goals that are more appropriate. Although this framework does not explicitly seek to produce rational behavior, an understanding of the information-processing constraints on scientific thinking can create conditions favorable to the use of more appropriate strategies.

This framework can also be applied to the cognitive-historical approach (Giere, 1988; Gorman, 1992; Nersessian, 1992; Tweney, 1989). Although the analysis of goals and purposes play a central role within the cognitively-oriented history of science, scientists' goals typically are analyzed at a fairly high level of abstraction (Tweney, 1989). However, consistent with Gooding (1992), the present framework assumes that goals influence scientists' behavior from the selection of a line of research to the moment-to-moment actions within the laboratory. For scholars (Giere, 1988; Gorman, 1992; Nersessian, 1992), who assume that mental models are the basic unit of scientific thought, this framework also has relevance. This framework assumes that models are constructed and modified within working memory. The ability to simulate the world is a distinct feature of mental models. In simulating the world, scientists can produce the type of dynamic changes that reflect changes in the states of the world. Gooding has suggested that thought experiments reflect simulations of mental models. Additionally, Gorman (1992) has argued that "a key component of Alexander Graham Bell's creativity was his ability to manipulate mental images, going back and forth between his evolving mental model of what he was trying to achieve" (pg. 203). During the simulation of mental models, the executive-control system selects which variables will be manipulated and what outcomes are produced. Finally, this framework can also explain why scientific revolutions are computationally difficult to explain. During scientific revolutions, scientists' mental representations undergo a major restructuring (Thagard, 1992). Radical conceptual change is computationally demanding because it does not involve merely adding or deleting individual concepts from one's mental representation. Instead, radical conceptual requires replacing an existing mental representation with an entirely new mental representation. Thus, constructing fundamentally new mental representations requires considerable resources of the executive-control system.

Several implications for computational models can be articulated as well. Although most computational models of scientific discovery include a control system, these models do not describe or focus on these processes. As Tweney (1990) urged, computational models need to consider the higher-ordered strategies. The role of executive-control processes can be easily examined within existing computational models. However, humans and computational models often diverge. As Chinn and Brewer suggest, most computational models of scientific discovery (e.g., KEKEDA, Kulkarni and Simon, 1989) respond to disconfirmation or anomalous data by revising the current theory. However, humans often ignore disconfirmatory evidence. Furthermore, computational models of scientific discovery, such as COAST (Rajamoney, 1990) and RED (Josephson and Josephson, 1994) generate competing hypothesis as part of the normal process of testing hypotheses. However, humans often do not consider multiple hypotheses. Thus, imposing the constraints suggested by the operation of the executive-control system may increase these models' psychological plausibility. Therefore, because of these advantages, further computational modeling of scientific discovery should include these constraints.

This framework also has three implications for future psychological research. First, although prior models (Klayman and Ha, 1987) provide a general explanation of the discovery process, the present framework allows for the specification of component processes. Second, like protocol analysis (Klahr and Dunbar, 1988) and problem graphs (Gooding, 1992), the present framework provides a method for the investigation of on-line scientific discovery. However, this methodology does not require the considerable time and effort needed to analyze individual's data. Thus, not only does an executive-control system theory of scientific discovery provide a detailed explanation of the process of generating and evaluating scientific hypotheses, it also provides a source for novel predictions and methods. Third, this framework can be used to explain other cognitive processes crucial to scientific discovery (e.g., analogical reasoning). The current framework can explain two important results of research on analogical reasoning. First, according to the present model, people typically do not spontaneously engage in analogical reasoning because although the mental representations directly related to the known domain are automatically activated, activation of knowledge of other domains requires controlled processes. Second, the construction of a new mental representation is an activity requiring considerable resources of the executive-control system.

8. Conclusions

Interpreting the strategic functions of the executive-control system provides a fruitful and comprehensive explanation of the cognitive processes involved in laboratory research on scientific discovery. Specifically, strategies (e.g., positive tests and single hypotheses) are selected to achieve the individual's goals while attempting to minimize the necessary resources. Considering explicitly-stated MH results in greater efficiency, more negative tests, and more disconfirmation. Thus, present framework provides an explanation of the processes of rule discovery.

Viewing scientific discovery as being directed by the executive-control system has several significant advantages for current computational and philosophical models. First, this perspective allows for a reconceptualization of scientific discovery. Rather than viewing discovery as an automatic process occurring outside of direct conscious control (cf. Simonton, 1988), scientific discovery is influenced by the deliberative and controlled processes of the executive-control system. Epistemologically, considering MH enhances the establishment of well-founded knowledge because the executive-control system activates the goal aimed towards the evaluation of the hypotheses' necessity. Third, the present framework allows for the investigation of on-line scientific discovery. Fourth, although computational models (Cheng, 1990; Kulkarni and Simon, 1998) have included strategies for the generation and evaluation of MH, imposing the constraints of the executive-control system will result in greater psychological plausibility.

Finally, although this framework has been derived from laboratory research, the executive-control system likely plays a greater role in actual scientific practice because scientists place enormous mental resources into their research. Indeed, when we move out of the psychology laboratory and into real science, the complexity and magnitude of mental processes increases exponentially. Therefore, the executive-control system is more vital in this context.

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