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Leonard F. Koziol

The Myth of Executive Functioning

Missing Elements in Conceptualization, Evaluation, and Assessment

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To Tim, who reminded me that success leaves behind clues; to Matthew, who reminded me to never, ever quit; to Peter, who I am sure will leave behind many clues as he climbs his ladder of success; and to my brother Ray, who taught me how to play chess and who gave me an inspirational quote that has helped drive my career.

—LFK

"Out of intense complexities intense simplicities emerge."

—Winston Churchill

"Every problem has in it the seeds of its own solution. If you don't have any problems, you don't get any seeds."

—Norman Vincent Peale

"Everything should be made as simple as possible, but not simpler."

—Albert Einstein

"That is the story. Do you think there is any way of making them believe it?"

—Plato

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Abstract

Volume II of this series on the vertically organized brain is devoted to the topic of executive functioning (EF). EF is examined within a metaphor of problem solving. Inherent in all problem solving is the ability to determine the stimulus-based characteristics of the problem. This book posits that because within neuropsychology, there is no universally accepted agreement on how to define EF, the reason for this confusion concerns an inability to discover the stimulus-based features of EF. This book proposes a simple definition of EF. This definition can be applied across 500 million years of the phylogenetic development of the vertebrate brain. After reviewing basic evolutionary, neuroscientific, and neuropsychological evidence, the book concludes that neuropsychology relies upon an unnecessary construct featuring different components related to thinking. Within that context, the "executive" within "EF" is irrelevant. This book generates a radical paradigm shift. It proposes that thinking developed to serve the needs of interactive behavior in which thought does not necessarily play a central role. The critical importance of movement and the ability to control interaction by anticipating the outcomes of actions are the primary components of thinking. These components include both explicit and implicit forms of "cognition." The argument is made that adaptation features a combination of automatic behaviors, most of which are learned, that alternate with episodes of thinking on a continuous, ongoing basis because the brain evolved to serve the dynamically changing needs of interactive behavior. Both movement and thought are involved in a neurobiologically situated cognitive control system; this is likely an evolutionary extension of the frontal-basal ganglia and frontal-cerebellar motor systems. The neuropsychological evaluation of these processes is examined by emphasizing divergent thinking, procedural learning, and reward systems. The application of new test paradigms and tests are proposed.

Keywords Executive functioning • Cognitive control processes • Automatic behaviors

Introduction

These first three quotations were used to open chapters 2, 7 and 8 of Subcortical Structures and Cognition: Implications for Neuropsychological Assessment [1]. They are reused here because they have special relevance for Volume II of this ebook series. These quotes capture the approach that was taken to understand EF. The last quotation introduced the final chapter of the book, which captures the essence of where this volume ends. This volume is about problem-solving. It is about executive functioning (EF). However, it takes these complex topics and describes them in an "intensely" simplified way. This manuscript finds solutions to understanding these issues by simply reflecting upon the obvious "seeds" of the problem. The answers to the questions that arise when trying to understand EF actually emerge from the questions to begin with! In any field of clinical diagnosis, if you ask targeted questions, you are led to accurate answers; if you ask poorly formulated questions, you obtain incomplete, misleading, and even perplexing answers. As the mathematician Enrico Bombieri once said, "When things get too complicated, it sometimes makes sense to stop and wonder: Have I asked the right question?" This paper is biased in believing it asks the relevant questions, and the answers that emerge are quite remarkable in their simplicity and consistency. Over 500 million years of phylogenetic development of the vertebrate brain can be understood within this model. And within the model that is proposed, there is no need for an artificial construct such as EF. The author anticipates this conclusion will generate considerable controversy. But observations from neuroscience make this "story" believable.

The paper was written for anyone who has a fundamental understanding of neuropsychology, the study of brain-behavior relationships. It was not intended for the advanced neuroscientist. However, sophisticated principles of neuroscience are applied to the study of behavioral control in a foundational way in order to help the field of neuropsychology move forward. Anyone who practices clinical neuropsychology, at any level, will find the issues addressed applicable to clinical practice. The model of self-regulation presented here "fits" all cases imaginable. If the clinician understands this model, he/she is hard pressed to find "exceptions" to the rule. As a result, this discussion is fundamental yet innovative. It would be useful for the reader

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to possess a working understanding of the functional neuroanatomy presented in Volume I [2], since the current volume reuses many of the same principles.

Problem-solving is a fundamental component of behavioral control. This is because problems, by definition, always consist of some degree of ambiguity or novelty. After the specific, concrete features of this "ambiguity" are identified, that person is on the way to solving the problem. That viewpoint is not universally evident within definitions of EF. Nevertheless, understanding the fundamental aspects of problem-solving is important because in general, problem-solving is inherent in managing the issues for the world within which we live. We are confronted with problems on a daily basis. These problems vary only in degree of complexity. As proposed by Toates [3] and as applied by Koziol and Budding to the field of neuropsychological testing [1], all problem-solving can be conceptualized by a very simple principle. At base, problem-solving is essentially the process of identifying the stimulus-based characteristics of an unfamiliar or novel, ambiguous situation. Understanding and manipulating these stimulus-based properties, a process often referred to as thinking, generates the solution to the "problem." The process often involves divergent thinking, or, using objects, or even "ideas," in a way that is different from their original intention. This also represents the thought manipulation that assists in identifying the stimulus-based controls that are applied in finding the solution to the problem. Since EF is an issue currently characterized by ambiguity, complexity, and a lack of consensus, examining EF within this problem-solving metaphor is a logical approach to follow.

Problem Solving: Practical Examples and Additional Properties

Under a variety of circumstances, breaking down a problem or reducing it to its stimulus-based properties might seem easy, and as a result, a solution can be found very quickly. For example, once it is understood that solving the arithmetic computation of 82–38 requires the application of a procedure of regrouping numbers by "borrowing" and "carrying," finding the answer is simple. The exact same procedure is applied each and every time; only the content or numbers of the computation change. When learning how to read and spell, after it is understood that in the English language, the letters of the alphabet can take-on more than one sound and that these letters can be grouped together to generate additional speech sounds, the processes of reading and spelling become easier (which really means the rules of reading and spelling are learned) and in the future, for most of us, reading becomes automatic. The exact same "rules of reading" are applied to whatever we read. The same general concept about problem-solving is true for all circumstances imaginable. If the stimulus based properties of a problem can be found, they can be applied, and a solution can be generated and learned. Once the solution is learned, the application of that solution frequently becomes automatic or implicit, depending upon how often a similar situation is encountered. The process is applied without giving the matter a second thought.

This is very much analogous to a "Zen" story. When a centipede was questioned about how he was able to coordinate all of his numerous appendages without appearing clumsy or stumbling, the centipede said that he had never given it a thought! However, from that time on, the centipede was unable to move! The point is that we learn many adaptive, common skills throughout our lives; these skills become automatic and they are not easily accessible, and sometimes not accessible at all, to the processes of conscious cognitive recall [4, 5].

An experienced neuroradiologist will view an ambiguous MRI or CT scan and quickly determine whether an anomaly on an image is a small tumor or a benign finding [6]. An experienced chess player can look at a configuration of pieces on a chessboard and quickly determine if these pieces are arranged in a pattern for a potential checkmate; the stimulus-based controls, which consist of imagining various sequences

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of moves, then leads to the proper move order to reach the goal [7, 8]. An automobile repairman uses a set of diagnostic tools to quickly determine why a car's engine will not start before making an attempt to repair it. A mover can look at a large piece of furniture and a doorway and then instantly determine, perhaps intuitively, the proper angle for moving that furniture through the opening, before "tinkering" with different angles and positions to see if the furniture fits. It is true that these examples might rely upon different learning systems, and that all of these systems will not be discussed in this book. However, in each and every one of these examples, the key issue concerns identifying the stimulus-based properties of the situation.

Similar problem-solving is involved in interpersonal situations. For example, since you know the preferences of your "significant other," you use that stimulus based information to make a pretty good guess as to whether or not they will like a present before you purchase it. This information about preferences allows you to *anticipate* their reaction. Therefore, this anticipation guides what you do. Without that type of information, your choice in decision-making can easily go wrong. For example, you might randomly decide to take your first date to a seafood restaurant. However, sitting together at a romantically arranged table, with the ambience of the restaurant seemingly perfect, your date reluctantly informs you about their allergy to shellfish and the fact that they simply are not partial to eating fish! At least you have acquired information about the other person's "reward" preferences, so that the next time you are faced with the problem of restaurant choice, you decide upon an eatery consistent with food preferences. You can at least use that information to point your thinking in a different direction. Taking these examples just a few steps deeper, this type of anticipation starts to suggest that empathy might develop from this process of anticipatory thinking. A variety of situations exemplify one simple principle: problem-solving requires people to discover stimulus-response based controls to guide behavior. This involves relying upon what a person has learned through experience and then applying that information to the current problem.

It is also obvious that problem-solving does not always proceed smoothly or easily. Thomas Edison "experimented" with many materials in trying to develop a light bulb; he was not successful after his first attempt. Alexander Graham Bell imagined that transmitting sound through wires was possible, but he, too, encountered repeated failures before finding the right materials for making a telephone. Thomas Salk worked with numerous chemical compounds before discovering a successful polio vaccination. The Wright Brothers (and many others before them) experienced repeated failures before a few successful, low and brief flights in 1903. All of these people demonstrated motivation on a persistent basis. They did not quit. Solving these problems must have been rewarding for them. The principles of flight became understood through application of "Bernoulli's principle." However, this principle was published in 1738 for the purpose of explaining fluid flow dynamics [9]. The principle simply states that when a fluid flows through a region of low pressure, it speeds up, and vice versa. Applying this principle to understand how it might be relevant to flight required a process of divergent thinking—using an idea in a manner for which it was never intended. The principle was applied to explain the flow of air, instead of fluid flow. But even with improved technology, there were still numerous failures in attempting to fly across the Atlantic Ocean until Lindberg's successful flight in 1927. Some aviators failed because of navigational problems; others ran out of fuel. However, none of these failures had anything at all to do with a lack of understanding of the principles of flight. Instead, flying across the Atlantic introduced additional stimulus-based features of a problem. These new features required identification through imagination or anticipation; innovation was required to implement ideas that might lead to a solution. While the list goes on and on, even just these few examples illustrate another important point about problem-solving: it is not always easy to find solutions and when failure occurs, this typically means that *all of the stimulus-based characteristics of the problem have not been accounted for*, *discovered or are not yet fully understood*. A program for traveling to Mars is under consideration. Considerable information about living in outer space has been gathered from "shuttling" astronauts back and forth, spending time in space for many months before returning home, in the international space station project. However, how does one keep a human alive, traveling in space, for 3 years? What are all the necessary environmental characteristics about Mars that must be known before embarking upon such a risky endeavor? Without a doubt, NASA's Rover missions are providing answers to many of these questions, but numerous other problems must be anticipated, simulated and solved before such a spaceflight. Without drawing from an appropriate knowledge base, and without the ability to anticipate, how does a person even imagine the potential problems?

Without question, one of the most impressive feats of problem-solving concerns the spaceflight of Apollo 13; the explosion of an oxygen tank when traveling towards the moon, a problem that had never, ever been *simulated* or *imagined* previously, generated a cascade of problematic circumstances, with a chain of problems unfolding, with one problem leading to another. Even though the spacecraft was designed with numerous "back-up systems," an oxygen tank was venting out into space, essentially making these contingency systems useless. The loss of oxygen threatened life support systems; it threatened the generation of electricity necessary for maintaining each and every vital system required for spaceflight, such as computer and navigation systems, communication between earth and the space vehicle, the fuel for using engines for course correction, temperature regulation, and so on and so forth. Each problem had to be solved correctly by "improvisation," by directly *interacting* with it, as these issues developed; other problems had to be quickly anticipated in order to take appropriate proactive steps immediately, because the nature of the circumstances did not allow the luxury of repeated problem-solving attempts [10]. The stimulus-based properties of the problems that arose had to be determined "on the spot," without overlooking a clue, because literally, "failure was not an option." However, many people, even including top-level NASA engineers, knew and feared it was clearly a distinct possibility [11, 12]. All sorts of practical matters had to be *anticipated*, such as how to conserve fuel, electricity, limited battery power, and oxygen; how to navigate correctly and change course appropriately without the luxury of a computer; how to conserve other supplies, etc; the list of issues is too long to mention here, but the point is obvious; problem-solving, and decision-making, involve the anticipation of outcomes. The "bottom line" is the kind of anticipatory thinking that should tell us, "*If I do this,* *than that should happen.*" So anticipation is inherent in solving problems; behavioral controls always predict or "look ahead."

Also, the engineers at NASA did not have the privilege of living in today's world of competitive academia in which they could receive the special accommodation of "extra time" in order to find the correct answer to a test question. The fact of the matter was that time was an extremely critical issue. Factual knowledge was one important variable. However, applying that information quickly, efficiently, and effectively, by directly interacting with the problem and *anticipating* the outcome was at the heart of the matter. In many if not most situations, *interacting with the problem in* the "*real time*" of the moment is a critical factor that is frequently dramatically revealed in problem-solving and behavioral control. The world we live in requires us to interact.

Speed of response is frequently critically important. Captain "Sully" did not have "extra time" to determine how and where to land a commercial jetliner in the Hudson River after the plane's engines failed [13]; an "ER" physician or "triage team" does not have much time to identify, prioritize, and treat an unconscious patient's injuries when the person is wheeled into the emergency room of a hospital after being in a motor vehicle accident. It should come as no surprise to anyone that pilots and those in "first responder" professions frequently train in simulation drills to make certain responses become *familiar, routine, and automatic.* This allows them to respond quickly and implicitly, even outside of conscious awareness, without giving certain matters a second thought. This then provides the opportunity to attend to the *novel* or more unique characteristics of the situation in question. Perhaps any job that initially prepares a person through "on the job training" serves a similar purpose.

Even these "quick action" features of behavior are also seen in a simple way at a very practical level; as you approach an intersection while driving and the light turns from yellow to red, there is little time to decide to brake; you are then glad you did when you see a "semi" speeding through the intersection from the opposite direction, or perhaps out of the "corner" of your "round" eye, you see a person who prematurely began to cross the street. Fortunately, we have learned a response to these situations! The ability to make certain choices and decisions automatically after we have sufficient practice is another critical feature of problem-solving. As noted by Richer and Chouinard [14] the best way to evaluate the efficiency of the fronto-striatal system is to observe its functioning under time pressure, and this is one of the "vertically organized" neural systems involved in behavioral control.

So, what is the point of reviewing so many wide-ranging examples? It is remarkable what problem-solving situations have in common, from making seemingly simple choices to the most advanced phenomenon, because inherent in all problem-solving is decision-making. In a sense, understanding decision making behavior is at the heart of this paper. It is truly remarkable what can be learned about decision-making by merely examining the obvious. Problem-solving is evident *everywhere, and these examples were chosen intentionally to illustrate different aspects of decision making, or different aspects of behavioral control.* These examples will be revisited later in order to examine subtle but significant differences and the cognitive networks that need to be flexibly recruited to function in these situations.

The Problem Solving Metaphor, Neuropsychology, and Executive Functioning

So, how do these examples and principles apply to EF as it is currently conceptualized in neuropsychology? The understanding of EF is a critical problem. Clinical practitioners and the educators who train them struggle with the issue of conceptualizing EF and the solutions to understanding what EF is, how EF develops and operates, and how it should be assessed is not coming quickly. There is no universal agreement in the field as to how to define the term “executive functioning” [15, 16]. Barkley [17] and Wasserman and Wassermann [18] have stated there are 18 definitions of the term. It is generally accepted that executive functioning is an umbrella concept that consists of several subcomponents. However, not everyone agrees about what and how many subcomponents there are and how they should be measured. Even when fractionating EF into elements such as “working memory,” “inhibition,” “planning,” and “shifting cognitive set,” there are no universally agreed upon definitions of these subcomponents. Therefore, the way these constructs should be operationalized in assessment is not standardized so different clinicians use different tests. Many clinicians use ready-made “batteries” of EF testing which likely makes the practitioner feel secure. However, some of these subtests might be based upon logical but nevertheless unwarranted assumptions. But the practitioner might believe that the assessment of EF was systematic and complete because the test manual says so. Certain tests of EF seem to be grounded in logic that has not been supported by neuroscientific evidence. When we administer a test of EF, do we know what brain regions are activated? Some tests that are pathognomonic of deficit are statistically converted into the standard scores of a normal distribution of a bell-shaped curve which then makes interpretation difficult. Why should a behavioral sign that is specific to deficit be “forced” into a statistically derived “score” that masks the behavior’s meaning? This might be useful for research purposes, but what meaning does this have clinically? Scaling techniques translate functions and processes into descriptive terminologies such as borderline, low-average, average, and high average, even though these terms provide no meaning at all for understanding a person’s practical functioning. What does it mean to have “average” or “high average” scores on subtests of EF? Tests used to assess EF are blatantly explicit. Is the EF

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observed in "real life" always so transparent? If not, what implicit functions and processes contribute to EF, and how should they be evaluated? Constructs such as "inhibition" and "disinhibition," which can be critical to understanding behavioral control, are processes often treated as unitary entities. However, these functions have multiple roles [19], and there are different types of inhibition which are task dependent and mediated by distinct brain systems [20–23]. Therefore, what does poor performance on any given test of inhibition say about a person's EF? What is the ecological validity, or predictive power, of neuropsychology's tests of executive functioning? It has been reported and argued that neuropsychological tests of EF do not predict deficits in the behaviors of daily life, and that behavioral rating scale data observations are more strongly associated with predicting impairment in major life activities [24, 25]. This implies that observing a person's behavior in the "real world" environment tells us more about EF than performance on a standardized measure administered within an artificial testing environment. Isn't this conclusion simply a refined version of a principle that most of us learned in an introductory psychology course, informing us that the best predictor of future behavior is past behavior? However, behavioral rating scale data also have limitations and are vulnerable to inaccuracies for a variety of reasons [26]. Isquith and colleagues recommend the combined use of performance-based and rating scale measures for obtaining a more comprehensive understanding of a person's EF, but how do the findings that emerge from this combinational assessment generalize across "real life" practical situations? It is not at all clear as to what this approach tells us about the neuroanatomic underpinnings of EF [27]. If a functional neuroanatomy of EF cannot be identified and linked with performance-based tests and observational measures, how does the practitioner merge theory with practice? The field has managed to turn the understanding and assessment of EF into a complete mess.

Simply put, the field is characterized by a lack of specificity in terminology, ambiguity and disagreement, and a reliance on assumptions that are sometimes unwarranted. In applying a problem-solving metaphor, this means *the field of neuropsychology has not yet determined all of the "stimulus based" characteristics and properties of executive functioning*. Therefore, the test paradigms are insufficient and often inaccurate. Similarly, the field is arguably at a standstill in terms of trying to understand EF; it is not moving forward. In this way, the "EF" of the field of neuropsychology is stuck in an ironic, paradoxical position, faced with a problem it just cannot seem to work out, while at the same time, the concept of EF is at the heart of a clinical neuropsychological evaluation. It is time for us to pause and wonder if we have been asking the right questions.

At first glance, this seems like an ominous, unsolvable problem. However, this manuscript is proactive and constructive, although it admittedly violates tradition. It reviews and integrates information from the fields of neuropsychology, the various neurosciences, and principles of evolution and phylogeny because the stimulus based properties of behavioral control emerge from the subject matter or content of these disciplines. Bridging the gaps by considering information in this integrative approach can place the field at the "cutting edge" or "on the cusp" of making major breakthroughs in this complex area. Although this paper proposes a simple definition of EF, it's very complex functional neuroanatomy is sufficiently described to be understood and applied within the clinical situation. Paradigms for its assessment and measurement are generated and proposed. In the process, many of the assumptions upon which the field of neuropsychology is based are challenged. However, these challenges are necessarily critical to examine and review because if neuropsychology, the study of brain-behavior relationships, cannot claim an understanding of thinking and behavioral control as its areas of expertise, the entire field is headed in a direction that is awfully, terribly wrong. The clinical field is susceptible to a misdirection that could possibly end in its demise. The definition of EF proposed in this paper is very general. EF is defined as the behavior any organism engages in for the purpose of acting in its own best interest as a whole for purposes of survival [28]. However, of what clinical use is that level of simplicity? The doubtful, skeptical reader is urged to read on, anyway, to learn why this artificial construct is unnecessary and even misleading for understanding the functions of behavioral adaptation.

Neuropsychological Constructs, Assumptions, and Executive Functioning: Revisiting Principles of Brain Organization

In the 1800s, Dr. Paul Broca observed that patients with expressive aphasia, which is sometimes termed motor aphasia, had lesions in the anterior frontal lobe. Dr. Wernicke later reported that certain patients had an aphasia characterized by a primary comprehension deficit. These patients had lesions within the posterior lobes of the brain. However, both patient groups had one issue in common: in right-handed patients, the lesions were localized to the left hemisphere. Many years later, certainly in the 1960s and 1970s, when the study of memory was in its infancy, it was observed that patients with left hemisphere lesions had more trouble in learning new verbal material, and patients with right hemisphere lesions had greater difficulty in acquiring and remembering "non-verbal" material, such as learning and remembering newly presented designs. These and other related findings led to the idea that the left hemisphere was a language processor and that the right hemisphere was a processor of "non-verbal" and primarily spatial information. The performances on various clinical testing tasks were inexorably assigned to one or the other hemisphere. In this way, information processing became "fixed" and neuropsychological tests became "easy" to interpret. Neuropsychology and related disciplines adopted these ideas as a primary principle of brain organization. This is known as the verbal–non-verbal dichotomy of functioning between the left and right hemispheres. It has also been referred to as the language-visuospatial dichotomy of hemispheric organization. These inferences and conclusions made about brain-behavior organization were based upon a "lesion model." The lesion model demonstrated how a person functioned without that brain region that was damaged. This model was appropriate for the technologies that were available during that era.

When this dichotomy was observed, methodologies for investigating brain function were primitive by today's standards. In fact, this dichotomy was established and accepted as a primary principle of brain organization long before any meaningful functional brain imaging techniques were available. In the neuroscience of this century, it is well recognized that this artificial dichotomy is misleading. Today we understand that there is absolutely no evidence to support this dichotomy as a fundamental principle of brain organization. This principle of vertebrate brain

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organization is simply and unequivocally false [29]. The available evidence demonstrates that the distribution of hemispheric responsibilities is not nearly so clear cut. However, many people practicing clinical neuropsychology, not to mention people in other related professions and laypeople, continue to believe this artificial, misdirected viewpoint. Students are still taught this dichotomy in some training programs. Reports of clinical neuropsychological evaluations frequently imply belief in this dichotomy. This constrains the way in which we understand people and the direction in which we move in clinical research studies. This principle has proven extremely difficult to dispel. In a way, establishing a principle of brain functioning or developing and believing in an artificial construct is analogous to passing a law in the legislative system; once it is "on the books," it becomes extremely difficult to amend or repeal. Despite the volume and weight of neuroscientific evidence that contradicts this "principle," the field of clinical neuropsychology has never adjusted its thinking in a way that reflects this evidence. In fact, some practitioners continue to use a diagnostic label unique to neuropsychology, namely, "Non-verbal Learning Disability," or NVLD, even though the evidence does not support the existence of that "diagnosis" and actually advises refraining from using that terminology [30]. It is very difficult to update practices in many clinical professions. Some of the reasons why certain innovations spread so swiftly and others so slowly have been reviewed by Gawande [31]. However, that discussion is beyond the scope of this paper.

This volume explains what are currently believed the putative principles of brain organization and cites the appropriate evidence to support the conclusions. These conclusions should be generally accepted at least for the time being in order to move the field forward. Neuroscientific findings are emerging very rapidly, so that any accepted principle might be considered to represent an interim solution instead of a firm conclusion. However, many aspects of clinical neuropsychology seem founded on the development of simple artificial constructs and domains; the dichotomy of verbal versus non-verbal functioning is just one concept that is misleading in understanding brain-behavior relationships, let alone adaptation and EF. There is a significant danger to the profession in retaining and applying these types of erroneous, artificial, over-arching constructs. We compartmentalize our way of thinking, this becomes habitual, these types of artificial and poorly understood constructs reify, and we fail to reflect upon them so that this way of thinking limits our understanding of cognition and ability to drive the field in a forward direction [32].

Functional Domains, Unitary Constructs, and the Integrated Brain

The specific functional domains tested in neuropsychology include language, visuospatial functioning, attention, memory, executive functioning, and sometimes sensorimotor functioning. Sometimes domains are contaminated by attempting to measure combined concepts such as visuospatial or visuomotor integration. At times, domains of evaluation include auditory versus visual. But, is behavior really organized in the brain according to these types of domains? Of course not! The general concept of domains enables or assists us in organizing our thinking about behavior. There is absolutely nothing the matter with thinking in this way as a starting point for trying to organize cognitive and behavioral data, just so long as we remember the artificiality of these concepts. However, failing to recognize the artificial nature of this over-arching, generalized domain approach, along with the deconstruction of domains into different components, still leads to limiting our understanding and application of the concept that the brain, when functioning "on line" during the performance of any task, is always operating by integrating different functional brain networks. This was the primary theme of Volume I of this series. Different tasks require the participation of different functional brain systems. There is absolutely no functional brain imaging data, using neuropsychological tests as "probes," that contradicts the very general principle that various, specific brain regions are recruited and integrated for performing any specific task [33–35]. The most generalized functional architecture of the brain is characterized by cerebro-cortical, cortical-basal ganglia, cerebro-cerebellar, and basal ganglia-cerebellar reciprocal connectional profiles [36–40]. This provides the framework for understanding all behavior. Within this architecture, the concept of "functional integration" refers to transient, dynamic, context-specific interactions that convey information by way of subsets of anatomical connections. These subsets involve a limited group of brain regions engaged by a particular cognitive process. One way of studying EF in clinical neuropsychology fragments this umbrella term into constructs such as "working memory," "inhibition," "shifting," and "planning" [16, 41]. However, the objective neuroscientific evidence is clear in demonstrating that none of these constructs are monolithic, unitary entities [21]. They are all multiple component processes,

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dependent upon these distributed brain networks that function in a task-dependent way [23, 33]. The types of "EF" domains currently conceptualized in clinical neuropsychology are "intertwined." When measuring EF, or any aspect of it, we can never say anything about the "executive" independent of the task used to assess it [42, 43]. An "executive" has never been found because there is no executive!

When learning an adaptive activity, a sport, an academic task, a habit, or a leisure activity, the anatomic localization of the task changes as it is learned, with less and less dependence on the guidance of cognitive control as the procedures of the task are acquired and become automated [44–46]. Traditional neuropsychology has a static conceptualization of processes that are in reality dynamically changing as the task is performed and learned. The new "domain" of interest should focus upon the functional networks themselves.

Ignoring these integrated network systems and conceptualizing brain functioning and behavior in these domain-modular ways generates a false sense of security by making brain-behavior relationships seemingly easier to understand. This domain approach might make the practitioner feel "safe or comfortable," but at the same time, it biases and limits our understanding of brain-behavior relationships. It also restricts translational communication and research between neuropsychology and neuroscientific professions. The literature which describes how large scale brain systems develop across the lifespan and how the resultant neural network dynamics, or how these networks interact to generate adaptive behaviors, is rapidly growing. This "cutting edge" information has not yet been applied to the interpretation of neuropsychological testing procedures. However, the general and basic "network" concept is not "brand new." Within the field of neuropsychology, Mirsky and colleagues were among the first to attempt to view "domains" such as attention as multiple component processes, recruiting different brain networks, that warranted a systematic, component-level assessment for clinical neuropsychological evaluation [47–49]. Clinical neuropsychologists are not universally taught and trained to think and interpret neuropsychological tests in multiple component, "network," or brain system terms, even though this should be "the gold standard." This volume represents one small step in that direction.

Large Scale Brain Systems

The concept of large scale brain systems was reviewed in detail in Volume I of this series [2], which described a model of brain-behavior relationships using ADHD as proxy. Seven patterns of connectivity have been identified within the human brain by Yeo and colleagues [35]. These seven connectional systems appear to be very robust since they have been observed with remarkable replicability. The frontoparietal network, or FPN, is engaged during the performance of effortful cognitive tasks that require rules or information to be kept in mind for guiding behavior. This is equivalent to a cognitive control network. The ventral attention network (VAN) supports object identification, which includes contextual salience or aspects of "reward value" by identifying objects *and what they are used for*. The dorsal attention network (DAN) plays a primary role in the control of spatial attention, including attentional shifting, object location, and information about *how objects are used*. The VAN and DAN interact with the FPN in goal-directed behavioral control processes, so that in aggregate, these systems transform into an "action control" network. The visual network (VN) supports and interacts with the ventral and dorsal attention networks to sustain attention and to suppress attention to irrelevant stimuli. The sensory motor network (SMN) executes the motor activity programmed by these other systems. The limbic network (LN) interacts with these brain systems for the purpose of generating motivational and reward influences. Finally, the default mode network (DMN) is active when we are "at rest," doing nothing but thinking, imagining, or dreaming as our mind wanders and drifts. However, as soon as we engage in purposive cognitive tasks or behavior, activity within the DMN diminishes very considerably. The neuroanatomy and functional connectivity profiles of these brain systems, which includes connections with the basal ganglia and cerebellum, defining the vertical organization of the brain, were described in more detail in Volume I. Castellanos and Proal [50] also provide a succinct, useful anatomical and functional summary of these large scale brain systems. (The reader of this paper is very strongly urged to review Volume I of this series [2], and/or the provided references; a comprehensive understanding of these networks, and their dynamic interactions, is absolutely critical for establishing and applying the principles presented in this current volume).

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The Application of Large Scale Brain Systems to Practical "EF" Behavior: Revisiting the Introductory Examples

The introduction of this paper described numerous examples of decision making, or problem-solving. These examples warrant a close examination of the concept of cognitive control, how it differs in some of these examples, and how it is measured in neuropsychological evaluation. All examples required keeping information in mind for the ultimate purpose of guiding behavior. To reiterate, this is a task-dependent cognitive system, with a changing locus of control dependent on the task in question, an extension of the fronto-striatal motor control system [42, 51].

The frontoparietal network (FPN), also referred to as the "executive" control circuit, provides the underpinning for goal-directed behavioral processes; it also provides the flexibility necessary to manipulate information in response to changing task demands; this network guides decision making by integrating external information with internal representations, or thoughts and ideas, feelings and needs [50]. In clinical neuropsychology, this is often referred to as working memory.

It has become tradition to assess working memory with the Digit Span task, requiring immediate recall of digits (Digits Forward or DF) and repeating digits in opposite order of presentation (Digits Backward or DB). In this regard, it is critical to review what functional neuroimaging studies demonstrate about patterns of neural network activation when normal control subjects perform the task.

In a PET scan investigation of adult normal control subjects, Digits Forward (DF) and Backward (DB) [52] performance recruited an overlapping functional system consistent with the FPN associated with working memory [53]. This network included the right dorsolateral prefrontal cortex (DLPFC), the bilateral inferior parietal lobule (IPL), as well as the anterior cingulate (ACC); digits backward additionally recruited bilateral DLPFC, with higher levels of activation in the left IPL. The ACC, a region associated with effort and the monitoring of performance, exhibited increased activity with increasing task difficulty. These findings are consistent with what was reported about areas of regional activation in the performance on DB with fMRI imaging [54]. Cerebellar regions were also activated, a finding which should not be unexpected, since activation of the cerebellum is evident on nearly all working memory tasks, including verbal working memory tasks, and interacting

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with numerous brain regions across tasks as part of a "network" [55–57]. It has been demonstrated through neuroimaging techniques that the integrity of white matter tracts projecting from the cingulate through the cerebellar peduncles support sustained attention and working memory abilities as assessed by neuropsychological tasks [58]. This finding provides support for including the frontal-cerebellar circuitry network in the behavioral control system.

The medial occipital cortex, including higher and lower level visual processing areas, was robustly activated and this could not be simply attributed to "visual processing." The critical importance of this point cannot be overemphasized. As reviewed by Castellanos and Proal [50], the occipital cortex has never been considered relevant to ADHD, even though neuroimaging studies have repeatedly found differences in medial occipital cortex. The "visual network" supports and interacts with the dorsal and ventral attention networks. The medial occipital lobes play a role in orienting attention, maintaining attention, and in suppressing attention to irrelevant stimuli [59, 60]. Auditory processing has been demonstrated to follow the organizational profiles of these same dorsal and ventral attention systems. The ventral auditory pathway is involved in mapping sound to meaning; the dorsal auditory pathway, through its connections with the parietal lobes and frontal eye fields, plays a role in orienting visual attention towards spatial location [61]. This is a form of lower-level "action planning," in which the visual system is guided to a particular area of interest. In this regard, auditory and visual systems interact so that eye movement trajectories influence spatial reasoning through an implicit eye-movement-to-cognition link [62, 63]. It has been documented that primary visual cortex (V1) as well as higher level multimodal association areas receive projections from both visual and auditory sensory processing systems. This establishes the underpinning for the functional connectivity that supports implicit auditory-visual interactions outside of conscious awareness while simultaneously supporting cognitive control [61, 64–66]. These system interactions provide for a more holistic account for why both auditory and visual brain regions are robustly activated during the administration of the "auditory" Digit Span working memory subtest. Auditory information frequently and *implicitly* evokes images, to guide and focus attention, even when we are not consciously aware of this process [67]. Banish and Compton [64] provide a simplified review of the anatomic connections supporting these processes. This again illustrates the artificiality of the "domain approach" when trying to understand adaptive behavior. Simply put, the auditory and visual "systems" are not as independent as clinical neuropsychology (and perhaps the publishers of neuropsychological tests) might like to think. In addition, a study by Li and colleagues recently linked the processes involved in the DB task to the superior temporal gyrus, interacting with the ACC and fronto-insular cortex within the "salience" network that is part of the motivational system [68]. This finding makes perfect sense since effort is required to perform the task.

It is widely assumed that the FPN is similarly activated in children. However, there is a subtle developmental trajectory that unfolds from childhood to adolescence to adulthood. While this network is identifiable in children, it has been observed that older children fail to fully recruit this network on tasks requiring the mental manipulation of information. Instead, compared to adolescents, children activate more ventromedial regions including the caudate and insula; adolescents activate more diffuse regions of frontal and parietal cortices. This is an interesting finding because the caudate, which is very sensitive to environmental context, and the insula, a reward salience region, represent a neuroanatomic underpinning of a child's reactive context processing as described by Morton and Munakata [69, 70] and Chatham and colleagues [71]. Children can be notorious in demonstrating a dissociation between knowing and doing. Although they verbalize they "know" what to do, they often react to situational context. Adolescents activate more of the central components of the FPN, which corresponds with increasing cognitive control. Therefore, between childhood and adolescence, there is a more consistent activation of the frontoparietal network, followed by a refinement of these network regions between adolescence and adulthood [72–74]. Therefore, the point made by Wasserman and Wasserman about identifying the sequence of development of behavioral control skills and how to evaluate them at different ages is very well taken [18].

This is important information that provides clues as to why neuropsychological test performances often do not predict decision-making, cognitive control guidance in practical, day-to-day situations. In the practical examples provided about purchasing a present or decision-making of restaurant choice, the FPN should theoretically be activated. However, this is not sufficient to guide the decision making choice. What Miller and others have referred to as the "cortico-thalamic-hippocampal" network (CTH) must also be activated because semantic and/or episodic memories provide a critical contribution to decision-making [28, 75]. This is the case because knowledge must be retrieved from factual, declarative memory storage systems that reside within posterior cortices in order to guide the decision-making process. The actual decision, or choice, is based upon the "salience" or "reward" value information assigned to the "items" that might be chosen from information retained in the longer term storage of the declarative, semantic and episodic memory systems. (The reader who is not fluent in discussing the declarative memory system is reminded that this "system" is often divided according to the semantic and episodic memory components.) These recollected "items" might even implicitly evoke visual images to guide selective attention in the decision-making process [67]. Therefore, in the neuropsychological assessment of working memory, an important aspect of the EF decision-making process is simply not evaluated. Working memory, declarative memory, (semantic and episodic) are very clearly distinct, separate, dissociable processes [76]. Activation of the FPN does not necessarily recruit the CTH network or the medial temporal lobe memory system. An intact FPN, assessed by a blatantly explicit working memory subtest, says nothing about access to declarative memory systems, its specific contents, or the "reward value" or salience information associated with that content. All of these factors will influence the decision making process. Since the information retained in these systems necessarily contains information that is experientially unique to an individual, this will definitely contribute to difficulties in predicting a person's decision-making behavior. This is of particular relevance in assessing children.

For example, typically developing children demonstrate this remarkable difference between knowing what to do and actually doing it [77]. Young pre-school aged children, and even infants, can demonstrate certain inhibitory capacities and working memory processes within experimental settings [78, 79]. However, this does not imply that these children are relying upon these metacognitive capacities to generate or drive behavior. As stated, the FPN develops slowly, as do the declarative and episodic memory systems [80, 81]. Children behave on the basis of reactive context processing. They have a tendency to react as events occur in the moment, although this can include retrieving information from memory as needed for the moment [71]. As typically developing children reach the age of 8 years old, a dynamic shift starts to occur towards proactive context processing in which purposive goals start to control behavior, which is inherent in the development of stimulus-based behavioral control capacities. Morton and Munakata have proposed a very compelling argument of how the development of inhibitory capacities, active semantic memory capabilities, and working memory functions are very closely linked as a child develops increasing behavioral self-control which essentially defines the autonomous, independent functioning inherent in the self-control of behavior [69–71, 82–85]. Different skills and memories develop within different brain networks and these processes drive behavior. For instance, procedural, skill learning memory dependent upon the cortico-striatal, basal ganglia system develops early and before declarative memory [86]. Semantic memory develops almost in parallel with the acquisition of language, and is sort of the forerunner for the development of episodic memory [80, 81]. These brain systems develop along different trajectories, but there is no evidence to indicate these brain systems merge as part of an executive control system.

Instead, as reviewed by Munakata, Snyder, and Chatham [87], three key transitions are involved in the development of cognitive control. First, children develop an increasing ability to overcome habits by engaging cognitive control systems to appropriately respond to the contextual cues within their environment. Second, they slowly shift from recruiting cognitive control reactively, as needed in the moment, to recruiting cognitive control proactively, in preparation for needing it, as in readying to anticipate. Third, there is a shift from relying on environmental cues for engaging cognitive control to the self-recruitment of cognitive control mechanisms, at which time ideas, mental representations, and abstract goals generate autonomous behavior based upon the anticipation of outcomes. This corresponds well with what is known about the development of large scale brain systems; in young children, proximal cortical-reward circuitry connections predominate; during the course of development, these proximal connections weaken in favor of the development of strengthening connections between distal brain regions [88–91]. This developmental trajectory corresponds with increasing cognitive control and is consistent with the connectional patterns observed in the development of large scale brain systems.

In any event, even when knowing about the integrity of any given individual's FPN, practical decision-making, "EF" behaviors, cannot possibly be predicted with accuracy. In part, this is because the decision-making process requires recruitment of other brain networks which are not assessed by neuropsychological working memory tasks (The Digit Span task was chosen for review because it is commonly used in clinical assessment; other tasks, such as the experimental Sternberg and N-back types of procedures are also restricted to assessing the integrity of the FPN; although these other tasks recruit additional brain networks, these networks do not include recruitment of the CTH). The development and integration of multiple brain networks generates cognitive control, but this does not identify any merging of brain systems into an "executive." On the contrary, brain systems and functions remain dissociable.

The Working Memory Index of any of the Wechsler scales [92, 93] arguably represent "the" most popular way of assessing working memory in the fields of applied neuropsychology, clinical psychology, and school psychology. This is certainly the case for evaluating the pediatric population with the WISC-IV [92]. However, this index is problematic for several reasons. It is a composite quotient that is derived from two different multiple-component subtests, specifically, the Digit Span (DS) and Letter-Number Sequencing (LNs) tasks for the child version and the DS and Arithmetic subtests for the adult version. Combining the subtests together to generate a single score actually results in a loss of potentially meaningful data because the composite quotient hides or masks the fluctuations in performances which are the potential variables of interest [16]. Lezak and colleagues further state that "composite scores of any kind have no place in neuropsychological assessment" (p. 24).

On the WISC-IV, the two subtests not only require different processes but the scores are computed differently as well. As described above, the functional neuroanatomy of the Digit Span subtest reveals the activation of the FPN. However, in addition to the differences in which the two subtests are scored, what makes DF and DB different from LNs in terms of task performance demand characteristics? In clinic referred samples, how often do these two tasks that make-up the WMI generate similar scores? Most practitioners would likely agree that different levels of performance when comparing scores on these two tasks are the "rule" rather than the "exception." Perhaps it should be no surprise to anyone that for the WISC-IV, the overall correlation coefficient between these subtests is 0.49 for typically developing children [94]. This, of course, essentially means that the score on one subtest predicts the score on the other subtest about 25 % of the time in normal control subjects. This predictive power is less than the chance of a simple "coin flip." From a statistical point of view, these subtests obviously do not measure the "same thing." So, why do practitioners bother with the global WMI? And which subtest score is more accurate in depicting the artificial working memory construct?

Different practitioners have both logically based and intuitive interpretations for the lack of correlation. Practitioners likely have different points of reference for "making sense" of what these subtest score differences mean, but this can only result in idiosyncratic interpretation. However, asking a few "targeted" questions can lead to brain-related hypotheses that are worthy of investigation on the basis of identifying task demands and neuroscientific data. In the LNs subtest, numbers and letters are presented in a "mixed-up" fashion and the examinee is required to then say all the numbers first, in *numerical order*, followed by repeating the stimulus letters, in *alphabetical order*. Inherent in this task is the *assumption* that the subject "knows" the numerical system and the alphabetical system with letters and numbers in proper sequence; this is a seemingly "safe" assumption for almost all adults and typically developing school-aged children. Accepting this assumption, which is likely accurate in all but the youngest school-aged children and the most neuropathological cases, immediately introduces new variables necessary for successful completion of this subtest. This is another critically significant point. But what are these variables of interest? What are the "seeds" of the solution to answering this question?

"Knowing," or having automated the numerical and alphabetical sequences, allows for reliance upon an inherent "declarative memory" structure, which resides in posterior cortices, or a "procedural" sequence, which resides in anterior, premotor cortices, to support successful task performance. This establishes a framework or reference point for keeping numbers and letters in proper order, therefore allowing for different cognitive strategies for "clustering" and/or "regrouping" the letter and number sequences. Furthermore, reliance upon these declarative and/or procedural sequence structures need not be the product of conscious awareness. Declarative and procedural memory networks can provide implicit support. Neuropsychology has historically and inexorably adhered to the prevalent view which considers all active components of working memory are intentional and conscious. The clinical assessment of working memory is based upon the administration of tasks that are blatantly explicit. However, Hassin and colleagues reviewed five studies which demonstrated that working memory processes can, and do, operate unintentionally and outside of conscious cognitive awareness [95]. These cognitive processes operate automatically. These points are of critical significance. The knowledge of the numerical and alphabetical sequences can very well support a neuroanatomical underpinning to assist in successful task completion; this potential task support is *exactly* what is missing from the Digit Span subtest. It can be argued that knowing the numeric sequence is not of the same level of significance for successful task completion on the Digit Span subtest. Familiarity with numbers is arguably a sufficient factor, and knowing the automated numerical sequence might actually interfere with successful performance; the routine sequence actually might require inhibition, generating greater cognitive demand. In other words, while both subtests are expected to recruit the FPN, there is a subtle difference between task demands. However, these different features of the subtests have not been systematically investigated.

The WAIS-IV presents additional difficulties for attempting to assess the working memory construct. The functional neuroanatomic substrate supporting Digit Span performance has already been reviewed, but using the Arithmetic subtest introduces numerous problematic dimensions. The Arithmetic subtest does activate the FPN, and in particular, the parietal lobes. As reported by Glascher and colleagues, the Digit Span subtest clearly activates a different network than the Arithmetic subtest [96]. Meyers and Rohling [97] primarily localized Wechsler Arithmetic performance to the left parietal lobe, which has been generally accepted as a primary area of involvement in arithmetic computation. Overall, various neurologic and imaging methodologies such as PET, fMRI, and ERP reveal the activation of an extensive neural network anchored in the frontoparietal system, including regions of the basal ganglia and cerebellum. However, different variants of a widely distributed network are activated depending upon the exact and often subtle changes in details of the arithmetic task performed by the subject [98]. Therefore, the different subtests clearly recruit different brain networks going well beyond the contribution of the FPN.

Furthermore, as an individual transitions from mid-adolescence to young adulthood, initially evaluated with the WISC-IV and later assessed with the WAIS-IV, why would any examiner expect similar WMI scores, since the Arithmetic subtest is substituted for the LNs? This is a critically important difference for clinical evaluation. Individuals with neurodevelopmental disorders demonstrate different patterns of brain network activation as compared to normal control subjects during the computation of different types of arithmetic calculations [99]. In a fMRI study that compared 7–12 year old typically developing children and autistic children (ASD) with superior mathematical abilities, children with ASD demonstrated different activation patterns within the bilateral ventral temporal-occipital cortex (VTOC), including the fusiform gyrus, in the medial temporal lobe, and in the posterior parietal lobe during the performance of complex addition problems. The control group recruited increased activity in the left DLPFC. Activation patterns in the VTOC predicted superior abilities in the ASD group [100]. Patterns of brain network activation in adult outcomes of neurodevelopmental disorders has not been systematically investigated. Therefore, simply put, interpreting the WMI as a global index at "face value" presents interpretive difficulties at any age.

This nevertheless illustrates a significant point in revealing that neuropsychological tests do not necessarily capture the stimulus-based characteristics of the construct of "working memory" functions which should be foundational for decision making and problem-solving. This exemplifies what Cromwell and Panksepp [32] have emphasized about the danger of using seemingly useful conceptual categories that really have no discrete reality concerning how cognition is organized within the brain. Overuse, misuse, and underlying assumptions about terms such as working memory can constrain research efforts and even generate misinterpretation of both experimental findings as well as clinical test results. The fact that many commercially available neuropsychological tests, even after numerous "revisions" and/or "updates," remain developed from an a-theoretical framework that has no identifiable or known neuroanatomic substrate certainly is of no use in clarifying these matters [101]. In fact, the practicing clinician should find this approach to test development disturbing. Would a primary care physician attempt to interpret a glucose tolerance test, or would a neurologist interpret a finger-to-nose test without having any knowledge of the anatomic substrates of those tests and how they relate to symptomatic expression? The logic behind the WMI (and many other cognitive tests) makes it is impossible to determine with any certainty what has been measured. Interpreting tests without understanding their neuroanatomic substrates and how they correspond with behavioral expression is based upon intuition and or guesswork; this way of interpreting data only increases false positive and false negative error. This approach to test development and interpretation does not link theory to practice.

In other examples described above, it is very obvious that the FPN did not only require recruitment of the content of declarative and/or episodic memory systems. Revisiting the example of making an emergency landing of a jetliner in the Hudson River is particularly relevant. Anyone familiar with the operations of the FPN would be compelled to agree that this system should theoretically be activated during any landing, or for that matter, any emergency situation such as in treating the unconscious patient. When the airline pilot who made the emergency landing was interviewed, he clearly stated he was very familiar with the area and important landmarks. This provides evidence demonstrating activation of the medial temporal lobe memory network, which is actually a recognition memory system that supports semantic and episodic memory [86]. However, the primary issue in landing this airplane required *activity*. This situation clearly necessitated observation and *action control*. The ongoing training of pilots always includes "practice" in a simulator airplane; this serves the purpose of exposing the pilot to *procedures or activities* that are necessary to apply in routine and critical situations so that these *procedures* become automatic. In other words, activity, or procedural knowledge, is frequently a critical requirement in the application of stimulus-based controls for successful task performance.

The acquisition of these skills might initially require the guidance of the FPN, but once the skills or routines are learned, they are implicit. In fact, acquisition of motor and even cognitive skills are assessed by observing improvement in task performance and not through "declarative," verbally explicit processes [102]. These skills become "automatic" [103]. While emergency situations were chosen to make inferences obvious to the reader, the fact of the matter is that we all live in an environment that requires constant sensorimotor interaction [104]. Once again, the neuropsychological assessment of the integrity of the FPN says absolutely nothing about how any given individual successfully recruits or activates *procedural learning implicit memory systems* which are foundational to adaptation as we interact with a dynamically changing world. Even when things seem to be going smoothly, a situation can suddenly become unpredictable, requiring the application or modification of previously acquired procedures. As discussed by Madl and colleagues [105], human cognition is characterized by cascading cycles of brain "events." These cycles are dependent upon frontal-striatal and cerebro-cerebellar interactions. Most of this occurs outside of conscious awareness. The striatum is highly sensitive to situational context [4, 106, 107]; it "senses" the essence of the current situation, it interprets this context with respect to ongoing interactive goals, and through the process of cortical-striatal interactions, it selects the appropriate action in response [108]. While this is an implicit process, these "cognitive cycles" of interaction also require the momentary activation of conscious cognitive direction even as familiar situations unfold because no two situations, on any given day, are exactly alike. Therefore, brief episodes of conscious cognitive input act as sort of a "steering wheel" to provide behavioral adjustment. Behaviors that depend upon goal-setting, deliberation and planning, require multiple cognitive cycles, since even these higher-order behaviors require an alternation between implicit, routine behaviors and their adjustment;

nothing ever goes completely or exactly as planned. These recurrent cycles require the adjustments that are actually made by engaging the cortical-basal ganglia and cerebro-cerebellar vertically organized brain systems [106].

The FPN is critical in these interactions, particularly since the parietal lobes specify the parameters of action for frontal lobe motor, activity systems [109–111]. Since the control of activity is the critical feature of interacting with objects and people within the world, it would be nice to know how a person learns procedures to begin with. Just as a pilot “practices” in a simulator, neuropsychology might reconsider “practice effect” as a useful index for how a person learns through activity. However, the important point concerns the fact that traditional neuropsychology does not evaluate procedural learning systems, which is a critically missing element in the way clinical neuropsychology conceptualizes “EF”. As stated in the Compendium of Neuropsychological Tests (p. 679), “Results from practice surveys indicate that neuropsychologists typically use explicit rather than implicit measures as part of their routine assessment battery …; In short, current theoretical knowledge is not well integrated in clinical assessment, and, as a consequence, important information regarding patient functioning is likely missed.” [112]. This point cannot be minimized because the above “real life” examples indicate thinking *always* leads to activity. The premotor cortex retains or stores the most efficient representation of the behavior, so the frontal lobes are active in “action control” [113]. However, it is well known that many aspects of activity are implicit [114, 115]. Adaptive interaction with the world is efficient, and requires the support of implicit learning and memory systems that respond quickly. Neuroscientific investigation has identified *implicit* support for the guidance of behavior [95], Pezzulo [116–118] has described how procedural learning can even lead to conscious declarative knowledge, and Ashby and Maddox [119] have comprehensively reviewed how complex interactions between multiple learning and automaticity systems are now in the process of systematic investigation. A model of working memory based upon explicit conscious cognitive control is limited and focuses upon the neural networks supporting the encoding, maintenance, and retrieval phases of explicit working memory tasks [42, 43, 120–123]; the temporal dynamics of cortical-subcortical processes in these tasks have been mapped [124]. However, the processes necessary for constant interaction within a changing world go well beyond these boundaries. The stimulus-based properties of decision-making and the control of interaction include both explicit and implicit functional processes.

It is clear that people learn to interact with their environment “subconsciously,” or implicitly, outside of conscious awareness [125]. In two independent investigations, Eitam, Hassin, and Schul demonstrated that implicit learning is sensitive to the individual’s non-conscious goals [126, 127]. These studies even revealed that implicit learning can occur in pursuit of achieving goals within novel environments. Humans can learn and use complex patterns of information without intending to learn them and without being consciously aware of these patterns. Implicit learning is a motivated process because it serves the individual’s purposes and goals; it serves the needs of interactive behavior. The conclusion is offered that unconscious implicit learning processes are very likely responsible for considerably more human ability

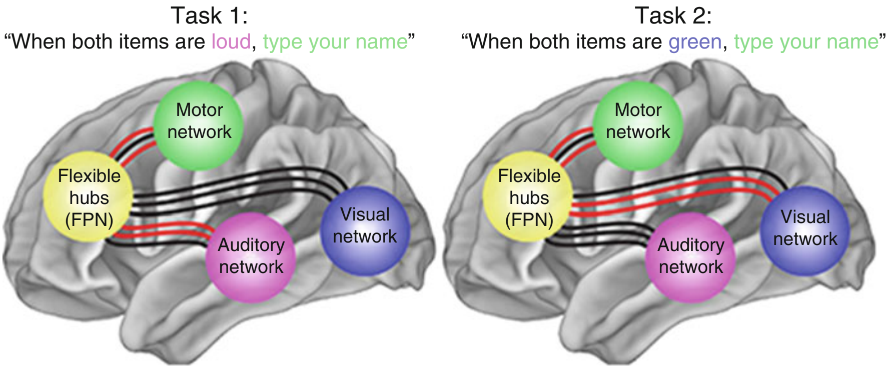

Fig. 1 The brain's FPN region is shown to play a central role in routing the processing of cognitive tasks among a range of specialized cognitive processing networks, such as the linkages shown here among the visual, auditory and motor networks

than is traditionally recognized. This is a key element, a stimulus-based property of cognitive control, that has never been addressed in conceptualizations of EF.

It is currently believed that the FPN operates as a "flexible hub" [128]. The brain regions that make-up the FPN very rapidly update their pattern of functional connectivity with other brain regions according to specific task demands. An inherent property of the FPN appears to be its dynamic flexibility in recruiting, or activating other brain networks across an extremely wide variety of tasks. In fact, when applying functional neuroimaging techniques, observing the brain network or system that the FPN recruited was successfully used to predict, or identify, the task that was being performed. There is no "executive" in working memory, and there is no "executive" in "EF." Instead, we find changing patterns of dynamic brain network interactions. In addition, the patterns of activation that were recruited were consistent across practiced or familiar, and novel tasks. In this regard, the reuse of these dynamically changing functional connectivity patterns becomes very efficient and conserves precious cognitive resources [129]. These patterns of flexible connectivity facilitate novel, adaptive task performance. The FPN functions in a critical role for "cognitive control," both *explicitly and implicitly*, for the adaptive execution of tasks as situations develop or unfold. It has been demonstrated that in children, working memory strength as assessed by an explicit task predicts both cognitive flexibility and speed of performance [82]. Since abilities dependent upon the FPN develop with age, it is likely that these same relationships between cognitive flexibility, and speed of task performance hold true for adults. The flexibility of the FPN is illustrated in Fig. 1.

The Novelty-Routinization Principle of Brain Organization

The verbal–non-verbal dichotomy of left versus right hemispheric specialization of brain function is problematic for several reasons. To start with, it is not biologically consistent across different species of the vertebrate brain. This dichotomy seems to emphasize the uniqueness of the human brain because of specialized language systems while ignoring phylogenetic continuity. Other primates make choices and decisions; they use tools, such as using branches for reaching, which implies imagination, anticipatory control and perhaps even divergent thinking in object usage. In a seminal paper by MacNeilage and colleagues [29], it was proposed that the left hemisphere of the vertebrate brain specialized for the control and execution of well established patterns of behavior under ordinary, familiar circumstances. The right hemisphere specialized for detecting and responding to unexpected stimuli. By de-emphasizing the role of language in hemispheric specialization, the authors traced the consistency of the novelty-routinization principle across 500 million years of the evolutionary development of the vertebrate brain. This is a dynamic principle that accounts for individual differences. For example, what is novel for one individual, as in learning a new task, might be familiar and highly routine for another person. This principle, in contrast to the verbal versus non-verbal dichotomy, argues against the fixed assignment of particular tasks to one or the other hemisphere [130]. The novelty-routinization principle represents a dynamic view of brain function, accounting for the changing functional neuroanatomy and locus of behavioral control that occurs during the course of learning and skill development [1]. Goldberg and Costa [131] were arguably among the first investigators to systematically review the structural and functional neuroanatomic substrates that support this principle. This principle is consistent with the rapidly emerging literature concerning the functioning of large scale brain networks. Finally, this principle represents an organizational system that allows for optimal, maximum flexibility in adaptation.

A critical feature of behavioral control concerns the constant adjustment to a changing environment. This involves the ongoing anticipation and adaptation of actions and the inhibition of inappropriate activities [132]. The level or degree of this control varies as a function of internal and external factors setting the task

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context [133]. The prefrontal cortex (PFC), important in aspects of this control and one of the regions of the FPN, also operates within this dichotomous principle. This has been well articulated by Goldberg and colleagues [134, 135]. The left hemisphere frontal system is critical for the individual's ability to guide behavior according to current cognitive context. The left DLPFC plays an important role in the FPN's ability for driving behavior according to the content of what one is thinking about for contextually-dependent behavior. The right DLPFC is important for cognitive selection driven by the external environment and for context-independent behavior. This highlights the role of the right FPN in processing cognitive novelty, in task orientation, and the generation of novel problem-solving strategies.

These functional differences have a neurobiologic substrate. Neuroimaging data reveal numerous structural differences between the left and right hemispheres [136]. These differences are found in language and motor areas, as well as in the visual cortex, parietal cortex, and hippocampus. These asymmetries developed in the early stages of evolution and are evident early on during ontogeny. Asymmetries are also observed in white matter pathways [137]. Electroencephalographic and magnetoencephalographic indices similarly reveal hemispheric asymmetry [138].

These hemispheric asymmetries are believed to support different modes of information processing. The right hemisphere processes information in a holistic and gestalt fashion and the left hemisphere processes information in an analytic, piecemeal fashion. This allows for the acquisition of complementary information about the world. Therefore, the two modes of processing provide "extra" or synergistic information, different than what would be obtained from one perspective alone, in isolation. The two hemispheres "filter" incoming information in different ways. The right hemisphere preferentially processes "low frequency" occurring information, and the left hemisphere processes "high frequency" occurring information [64]. This makes the right hemisphere sensitive to novelty, since by definition, novel information is new, unfamiliar, and of low frequency occurrence. At the same time, the processing of high frequency occurring information is, by definition, routine and familiar, so that this predictability is subject to management within a "coding" system. This system of information processing likely evolved because of adaptive advantage and for the preservation of neurobiological resources. This can be thought about in a very simple way. Information processing within one hemisphere transmits information to proximal brain regions within the same hemisphere; this information "travels" a shorter distance, consuming less energy and saving time which is important for exploiting the routine, predictable aspects of the environment. However, with novelty, information must be transmitted between hemispheres, to more distal brain regions, in order to find the stimulus-based properties of ambiguity. This information transfer "travels" a longer distance, which takes more time and more biologic energy. Therefore, hemispheric specialization evolved because it was more advantageous and economical. Task performance requires the participation of both hemispheres, but novelty, in particular, places high demands on hemispheric interactions, which helps to explain why finding solutions to problems for which a "ready-made" code is not available operates slowly. This also implies the advantage of automatic, routine behaviors that alternate with episodes of "cognitive control" for maximum benefit when interacting with an environment that is not always predictable.

Within this novelty-routinization principle, language is understood as a "specialized instance" of routinization. Language is a categorizer. It is a semantic system that allows us to manage stimuli within an increasingly complex environment. Semantic categories allow us to group commonalities of items together while simultaneously emphasizing their differences. For example, automobiles, trucks, bicycles, boats, and airplanes are all "items" for transportation, but they operate by different means and are used for different purposes. So even though they are alike, they are also different. This semantic classification system arguably supports the process of divergent thinking often necessary for problem-solving, even though these "items" are always context-dependent.

The rules of grammar and syntax never change, they are rule governed, and routinized through the processes of basal ganglia "binding" operations [139–142]. The neocortex provides the content for this grammatical structure. Right hemisphere contributions allow for the manipulation and integration of categorical information, facilitating divergent, novel thinking. The left hemisphere focuses on the individual "trees," and the right hemisphere sees the "forest." For example, the "Bernoulli Principle" explains the dynamics of fluid flow on the basis of changing pressure. This is a well known, concrete, predictable principle of physics; it is "routinized." However, because the right hemisphere can "take-in the whole scene," it becomes possible for this gestalt-type processing to set the framework for solving problems that might have similar, yet different characteristics. Even though flight does not involve any real fluid flow, it does involve air flow. The gestalt framework involves how pressure and the flow of a substance might be related. By designing the shape of a wing so that the air flowing past the top surface is moving faster than the air flowing past the bottom surface, this pressure difference results in an upward, lifting force. By changing the shape of the wing when the airplane is off the ground, we control flight because we alter the flow of air pressure dynamics around the wings. Similarly, we can develop the shape of a sail in order to move and navigate a sailboat by applying the same principles of air flow and pressure changes. We can apply that principle to control movement over water and in the air, which are "divergent" applications or "by-products" of a principle of physics that was never intended to explain the dynamics of air flow. In the process, we have also generated two new "objects" that fall within the semantic category of modes of transportation. New knowledge has been acquired through the interactions of both hemispheres. In these ways, semantic systems are not only important for language, but also for the manipulation of these categories for the divergent thinking often necessary for problem-solving.

For those readers who lack familiarity with the laws of physics (the reader should know by now that the author of this paper has preoccupying interests that color the examples chosen), perhaps other examples are in order. Just for the sake of illustration, let us acknowledge that many people were involved in making combustion engines and automobiles, so the following example is not historically accurate. That said, during the era of Henry Ford, the "horse and carriage" was a chief mode of transportation. Henry Ford knew of engines and motors; locomotives had engines to power trains to transport people. Both the "horse and carriage" and the train are in the same language based semantic category of modes of transportation. Henry Ford specifically used an engine for an automobile, a "horseless carriage." He thought in a divergent way to use an engine for a purpose that was different from the concept for which an engine was originally intended. This process required the interaction of the context-specific left hemisphere as well as the holistic thinking of the right hemisphere. This process also generated a new item for the semantic category of modes of transportation. The Wright Brothers, who worked with bicycles, a completely different mode of transportation, thought divergently to anticipate how an engine might propel an airplane, in order to apply speed to change the pressure dynamics of air flow, again manipulating semantic concepts for a purpose that was different from the original intended applications. In doing so, they expanded upon the semantic category of modes of transportation by adding the airplane. All of these once novel modes of transportation are now very routine, a "summary statement" which reflects yet another abstract application of the novelty-routinization principle. In any event, divergent thinking is often required in order to identify the stimulus-based properties required in problem-solving. This type of thinking is an underpinning of the development of our current technologies. This requires hemispheric interactions. The information processing properties of both hemispheres operate in a synergistic way, since these "discoveries" could not have been made when viewing the problems from the perspective of only one hemisphere.

This organizational principle is biologically consistent across all vertebrate species while it is biologically economical. Routine, "automatic" behaviors allow us to exploit the common, predictable aspects of the environment. We learn behaviors and apply them across similar situations and contexts. Without this ability, everything we experience would be "novel," and this would require tremendous energy expenditure; every time we did something, it would be as if we were doing it for the first time. Automation, and/or habit, actually generates the tremendous benefit of obviating the need to continuously allocate attentional resources to the performance of routine tasks, making "multi-tasking" a possibility [5]. On the other hand, the environment is not always predictable. New or novel situations need to be detected, and behaviors have to be modified, or new behaviors have to be generated and learned, in order to meet new, novel, demands. This often requires divergent thinking. However, these examples also illustrate how the determination of stimulus-based controls are applied in problem-solving. All aspects of adaptation are optimized within this principle of hemispheric brain organization. And, the anticipation of an outcome is inherent in each and every one of these examples.

The development and implementation of functional neuroimaging techniques has been profoundly changing our understanding of hemispheric specialization [143], and these changes have yet to be implemented in neuropsychological test interpretation. Kaplan and a host of others have described how most neuropsychological tests, including those measures traditionally thought of as "non verbal," recruit the functional processes of both the left and right hemisphere. In fact, functional neuroimaging data are overwhelming in demonstrating this point, as discussed above [144–146]. This is the case because most tasks are multiple component; testing tasks include features of novelty, but aspects of the task are usually also amenable to a predetermined or familiar semantic "code." For example, consider the task of drawing the Rey Complex Figure [147]. This is clearly a novel, complicated task as its name obviously implies. However, in drawing this design, the subject with "good" problem-solving skill will likely break the task demands down into its stimulus-based components, such as the Gestalt of a basic rectangle, horizontal and vertical lines, crossing intersecting diagonals, and various details such as a circle with three dots that some say resembles a bowling ball and others say resembles a face, and numbers of short lines that need to be copied to cross a diagonal. Therefore, the novelty, or problem solving inherent in the task, is successfully accomplished by using known, familiar "codes." Even this description of the task reveals it is hardly "non-verbal." So, in clinical neuropsychology, just because a task does not require an oral reply does not mean that the task is "non-verbal," and assigned to the processing of one or the other hemisphere. A similar conclusion is evident in examining the learning of a word list learning task.

For example, an fMRI investigation revealed that Trial 1 of the CVLT [148], the immediate encoding of words, activated not only left temporal lobe regions, but also right temporal lobe activation for novel words, as well as recruitment of the right DLPFC. Right hemisphere activation was particularly evident in those subjects with better overall memory ability [146]. Therefore, even within a "verbal" domain, there is an absence of evidence of a fixed left hemisphere assignment on a language-based learning task, and there is additional support for the novelty-routinization principle of hemispheric brain organization.

Therefore, it is critically important to understand this principle because it is at the very heart of adaptation and the determination of stimulus-based behavioral control. Over 500 million years of successful evolutionary adaptation presents an argument that has a very compelling supportive history. The field of clinical neuropsychology is overdue in applying this principle to test interpretation as the "gold standard" even though this principle was evident many years ago. In a nutshell, this paper proposes that successful adaptation requires both the execution of automated procedures and cognitive controls. Neuropsychological evaluation needs to incorporate tests of procedural learning in order to identify how people benefit from the experience of interacting with tasks. Furthermore, it needs to be recognized that procedural learning is not a unitary entity. In this paper, procedural learning is defined very broadly to include sensorimotor skill learning, cognitive skill learning, perceptual categorization, and even the learning of habits and routines; the basal ganglia and cerebellum appear to make differential contributions to these learning processes. (See [102] for a simple overview).

Clues to Understanding the Phylogeny of Behavioral Control

Any living organism has, by definition, *successfully* adapted to its environment. And, broadly speaking, *success leaves behind its clues.* Reviewing the “duties” of the vertebrate brain provides these clues. According to Ito [149], the vertebrate brain has five basic duties. These duties are common to all vertebrate organisms, from fish to humans. First, there are autonomic and somatic reflexes and second, there are compound movements such as posture, breathing, saccadic eye movements, and locomotion. Many aspects of these functions are mediated by neural activity within the spinal cord and the brainstem. Third, functions such as nutrient intake or feeding, drinking, “fight or flight” mechanisms, and sexual behaviors are all essential to survival and are mediated through the activity of the hypothalamus and limbic system. Many of these behaviors are innate and automatic, demonstrating the adaptive value of automaticity and the lack of the requirement of conscious cognitive control. The speed with which these basic functions operate is quite impressive. The fourth function of the vertebrate brain concerns cerebral, or cortical, sensorimotor activity, as observed in the development of birds and mammals. The sensorimotor regions occupy significant areas within the neocortex, while the activities of mammals, including humans, require the integrated interactions between the cerebral hemispheres, the basal ganglia, and the cerebellum. In this regard, large regions of the cortex are recruited when engaging in activities that are not “cognitive.” Fifth, cerebral association functions developed in primates. These functions, which include thought, are represented within approximately three-fourths of the human neocortex. While the cortex significantly expanded during the course of evolution, a parallel expansion is observed in the cerebellum, with increasing and new cerebro-cerebellar circuitry systems observed as we ascend the phylogenetic scale [150–154]. The expansion of the striatum is considered to be proportional to that of the neocortex in all vertebrates, but in the human brain, the progression of the neocortex greatly outweighs striatal expansion [155]. However, the striatum receives direct projections from all major cortical association regions with the exception of primary visual cortex. The ratio of inputs are as high as 20,000 cortical association neurons to 1 medium spiny cell striatal neuron [156]. This input

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anatomy provides a substrate for a wide variety of contextual information to be made available to the striatum, enabling the basal ganglia to generalize by recognizing patterns [157]. Finally, it is also notable that higher-order control functions which are presumably dependent upon the neocortex operate much more slowly [149, 158–162].

That said, how does this information provide clues about identifying the stimulus based characteristics of behavioral control? The answer is deceptively simple. Throughout the course of evolution, vertebrates have functioned with minimal reliance upon higher-order control processes. Cognition developed, or evolved, from "bottom up," and not from "top down." This type of adaptation is economical, it conserves resources that require energy expenditure, and the "automatic" nature of behavior allows for interacting with the predictable aspects of the environment. *Evolutions oldest solutions for generating adaptive behaviors do not involve sophisticated cognition or conscious cognitive control*. Evolution also *preserves* those mechanisms that are effective and adaptive, nearly all of which have been preserved in humans. As organisms developed, which is particularly evident in primates, the brain developed flexible learning and memory systems to learn new behaviors. These new behaviors solve novel problems. In evolution, new functions emerge by expanding upon existing structures. Each new level of function is capable of exerting modulation over older processes [3, 163–166]. However, the critical point is that recently evolved brain processes and functions co-exist with phylogenetically older functions instead of replacing them. This also implies the dependence of higher-order control processes upon more fundamental, lower-level systems and functions. In the neuropsychology of primates, *cognitive control systems cannot exist outside of the context of automaticity, and automaticity cannot occur without cognitive control*. Both must co-exist. This interactive capability is the essence of independent, autonomous adaptation [75].

Ways of Generating Behavior

Organisms are not stationary. Organisms must move! Therefore, adaptation is not static. Instead, it is dynamic. It is based upon continuous interaction with the environment. Therefore, adaptation is based upon movement. The vertebrate brain system is not passive; it does not just start to work when it is triggered by stimulus input. Instead, it has a very active capability that is independent or autonomous from adhering to the present. The vertebrate brain system can generate behaviors only in two ways; both of these ways of generating behavior are equally important and necessary. These ways of generating behavior are "standard operating equipment" that can be observed in every vertebrate species.

One way to generate a behavior is in response to a stimulus. The stimulus can be either external or internal. When an individual is hungry or thirsty, it is appropriate to eat and drink. The vertebrate brain can also tolerate delay, so that it can over-ride an immediate reaction; for instance, we are not bound to eat or drink the first appropriate nutritive stimulus we encounter. The second way of generating behavior can have little to do with immediate satisfaction. For instance, some behaviors require the establishment of purposive, shorter and/or longer-term goals. These behaviors almost always require higher-order control. This usually requires over-riding or inhibiting other response tendencies. To reiterate, automatic behaviors conserve energy and therefore, these behaviors are economical. Certain behaviors are innate, such as reflexive sucking, feeding and swallowing. It is interesting that these behaviors predict later neurodevelopmental outcomes, including the integrity of higher level cognitive functions [167]. However, other behaviors which are equally automatic must be learned. These behaviors run on the basis of acquired associations. When these behaviors are repeated or practiced, they become routine. In fact, if we did not have this flexible capacity to function on the basis of acquired associations, we would be unable to live in "real time" because conscious, cognitive control operates slowly. It also requires considerable energy expenditure. As new behaviors are repeated and learned, they become effortless and independent of higher order control [129]. This process is associated with a changing neuroanatomy that governs the behavior [46, 157, 168]. It has been estimated that perhaps 95 % of an adult

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human's activity or behavior is routine and automatic, outside of conscious cognitive awareness and voluntary control [114, 115, 169]. As stated by Saling and Philips [170], automatic behaviors are quickly executed, they are very often elegant, and, in the proper stimulus based situation, they "work" or are adaptive each and every time they are executed. These types of behaviors are certainly not "mindless," even though they are implicit, usually outside of awareness. So, in adult adaptation, higher order control does not appear to be necessary very often.

Cognitive control systems and learning processes are not unique to humans. Animals can imagine and compare different navigational pathways before choosing a route to follow; they can select from certain short-term and long-term goals; they can both predict and avoid certain dangers [171]. Certain species of primates use tools, which means they plan and think ahead, which are really forms of anticipation [172, 173]. This reveals a cognitive control system. The continuity that is observed implies that the cognitive behavioral control system is an *evolutionary extension of the cortical-basal ganglia and cortical-cerebellar motor control systems.* These two vertically organized systems are identified and operative in every vertebrate brain. As phylogenetic development slowly encountered increasingly complex demands, this must have placed considerable pressure on these vertically organized brain systems to learn to interact with an increasingly complicated environment.

Movement, Thinking, Anticipation, and Banishing Executive Functioning

As stated in Volume I, the functional architecture of the vertebrate brain evolved to meet the needs of interactive behavior; it did not evolve for the specific purpose of thinking [104]. This evolutionary phenomenon was very strongly conserved throughout the course of phylogeny. This principle is evident in fish, birds and other mid-sized mammals such as cats and dogs, non-human primates, and in humans [149]. The needs of interactive behavior require continuous neural processing. This neural processing occurs within seven large scale brain networks which develop slowly in human beings [2]. These networks process or "code" the salient properties of objects, such as what they look like and feel like, as well as what they are used for, which in essence is their reward value. All of these properties are represented in the same sensory and motor brain circuits that were activated or recruited when the information about the objects was initially acquired [174–178]. In brief review, the ventral stream of information processing registers what an object is and what it is used for, which is another way of saying it "codes" its identification and salience, or reward value. The dorsal pathway registers where an object is and how to use it, in other words, specifying the proper parameters for action; these streams of information processing are therefore critical for "action" control. Salience information "biases" potential behaviors by providing information about reward value associated with the identity of the object. This "biasing" about reward value is essentially a form of anticipation or prediction [179–182]. We "know" that when we "interact" with an object ("object" is defined as a person, a thing, a nutrient, or an animal) that there will be a certain outcome that has a certain purpose or meaning. Several potential behaviors are available in most circumstances. Choices and decisions are made on the bases of anticipated reward—either obtaining satisfaction or avoiding a negative outcome. However, the point of the matter is that potential activities, choices, or decisions are represented over large regions of the cerebral cortex. Therefore, decision making is not strictly localized within the prefrontal cortex, nor is it localized within the FPN; instead, these functions are localized within the same sensorimotor circuits that were activated when processing the information, when associating that information with reward value, and when

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programming and executing the associated actions. These organizational characteristics allow for adaptive functioning characterized by routine behaviors as well as the learning of new responses. Automaticity and adapting behaviors across similar contexts is achieved through the operations of the cerebro-cerebellar circuitry system [183]. The learning of new behavior is supported by the reward based instrumental learning cortico-basal ganglia system [184]. These systems, in combination, allow for a level of functioning characterized by alternating episodes of automatic behavior and cognitive control. Therefore, "cognition" is not separate from sensorimotor control [104, 185]. The "locus of control" over interactive behavior is a dynamically changing process. There is no "executive functioning" in this system of behavioral organization because there is always decision-making and problem-solving based upon multiple options. The behavior that is either explicitly or implicitly chosen is based upon "reward value." This interactive paradigm is illustrated in Fig. 1 (Cisek and Kalaska illustration).

Knowledge for all behavior, and about rewards, for all organisms, is derived from sensorimotor *anticipation* [109, 116–118, 186]. *Sensorimotor activity is never random* [187–189]. Even primitive and transitional reflexes, the earliest observations of purposeful movement, mediated by brainstem and mid-brain regions, are associated with the anticipation of an outcome. Behaviors such as "latching on" and reflexive "sucking cycles" anticipate the outcome of nurturance. It is no accident that deficits in these behaviors are associated with future neurodevelopmental abnormalities [167]. This also implies that the development of higher level brain systems require the integrity of "bottom-up" support. There is a voluminous literature, well beyond the scope of this selected review, which demonstrates the inexorable relationship between motor anomalies and cognitive control deficits (for summary reviews, see [110, 190, 191]). The fact that movement is never random is not only evident in neurodevelopmental disorders but in other and disease processes as well. For instance, in Attention Deficit Hyperactivity Disorder, the release of primitive and/or transitional reflexes is often observed [166]; Huntington's disease is characterized by the release of fragments of purposeful movements [192]. Cognitive control deficits accompany movement disorders and neurodevelopmental pathologies [193–195].

The importance of movement for the development of the cognitive control system is based upon three principles. First, an individual's knowledge and representational ability is derived from interaction with the environment, in other words, sensorimotor *interaction*. Second, reusing sensorimotor learning mechanisms (throughout the course of evolution) can lead to the development of both procedural and declarative knowledge. For example, the *anticipatory* mechanisms that are relied upon in the control and execution of behavior generate procedural, or "action" knowledge. This includes knowledge about reward value. Re-enacting these neurobiologically situated actions and behaviors, through imagination or mental simulation/emulation (which also can be thought of as "thinking," remembering what one did and what happened as a result of that behavior, or rehearsing in one's mind), can produce or generate declarative knowledge. Third, imagining the *results or outcomes* of these prior activities, and internally manipulating this information, generates cognitive control, because this includes information about rewards. In other words, the

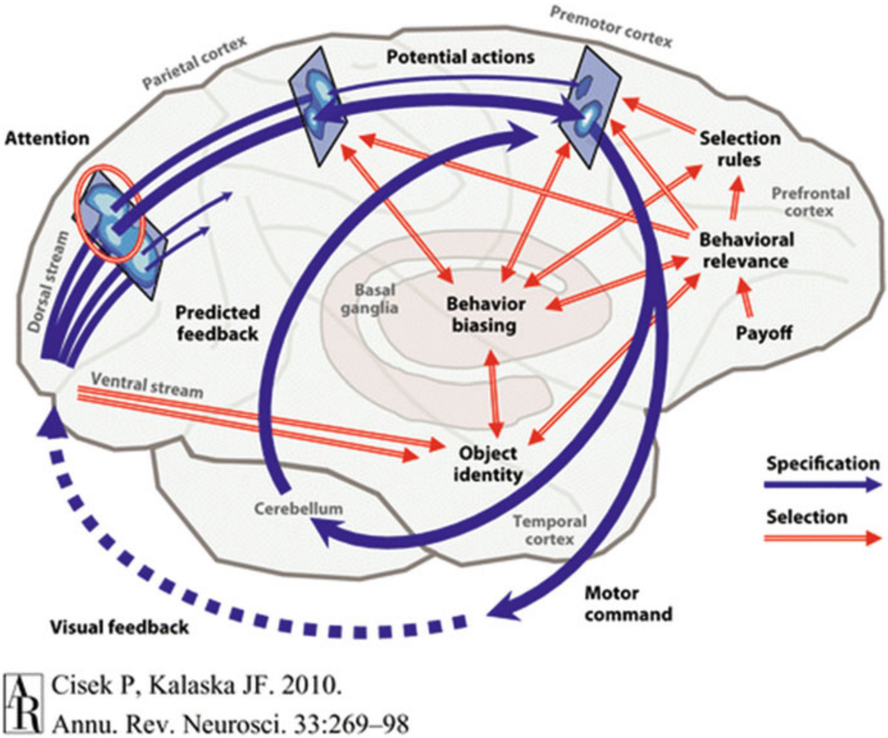

Fig. 1 This diagram represents a sensorimotor interaction paradigm for visually-guided movement, illustrating interactions between the cortex, basal ganglia, and cerebellum. The dorsal stream (DAN), which consists of the parietal cortex and reciprocal connections with the frontal eye fields and premotor regions, is concerned with practical representations or programs for the opportunities for action that situations offer. The *dark blue arrows* stand for action specification, which are all the parameters for the performance of the behavior. This processing originates in the occipital lobes (VN) and proceeds in a rightward direction through the dorsal pathway. This dorsal pathway registers not only where something is, but also 'how to do' something, such as how to grasp, as might be determined by an object's shape, size, and movement. This region plays a critical role in the procedural memory for action concepts. The ventral stream (VAN) serves object identity and reward value. When interacting with the FPN, this becomes an "action control" network. (All connections are not directly illustrated; see text.) The *polygons* represent three potential actions (neural populations) along the dorsal route. Competition for action choice or selection is biased by "reward center" input from the basal ganglia to parietal, temporal, and prefrontal neocortical regions. *Reciprocal red arrows* represent this evaluative biasing process. Therefore, action choices are represented over large regions of cerebral cortex and subcortical regions. The action that is selected depends upon the behavior with the strongest bias. The cerebellum (*blue* and *dotted blue arrows* connecting the cerebellum in this drawing) adjusts behavior on the basis of anticipated or predictive outcome which is inherent in cerebellar control models (Color figure online)

cognitive control system is derived from, or grounded in, the anticipation which is inherent in interacting with the environment [116–118, 196, 197].

Anticipation, an inherent design characteristic of the brain, is important because of its relationship to reward value [198]. Therefore, since interacting with the world (defined as interacting with objects and/or people) occurs all the time, anticipation is similarly ongoing and continuous. Since anticipation generates decision making based upon some level of reward value, anticipation includes a type of "wager" or "bet." This wager is based upon the individual's prior experience. Its purpose is to "ready" or prepare a response to an event that has yet to occur. It is sort of a "fortune teller" that is relied upon to control action. It is a process that can occur implicitly or explicitly, with or without conscious cognitive awareness. It is the driver of all behavior. It can be seen in every activity we engage in, from the most basic activities of daily living to the most complex conversational discourse. In this way, it can be understood as occurring along a continuum or hierarchy [199]. It provides a critical and deeper understanding of the cognitive control system. It is a system that believes, *if I do this*, *than that should happen*.

Because these concepts are so critical to the development of behavioral control, examples are in order to thoroughly understand their significance. Several important examples have been given by Pezzulo [116–118], but the content modified and substituted here serves the purpose in generating an understanding of the basic ideas. For instance, consider the individual who enrolls in a vocational school. The "anticipatory wager" or the controlling influence is the expected outcome of becoming a certified automobile mechanic. That person participates in "on line" training with "hands on" experience of working on an automobile engine. That student eventually learns to disassemble and reassemble that engine "in his head." This is essentially an imaginary, "off line" simulation of the process of working on a car engine. The cognitive re-enactment of this process, or thinking about what was done, can lead to the development of declarative knowledge; the learning of a procedure (assembling an engine) has generated declarative and semantic information about engines. Now this newly acquired information can be used in an anticipatory way again, not only for the problem-solving needed to repair an automobile, but perhaps for the purpose of designing an improved engine. So this entire scenario is based upon the anticipation that "if I do this, then that should happen." This is how we control action, or what we do. The personal experience gained from attending the vocational school has prepared behavioral responses to events that have not yet occurred.

This type of knowledge acquisition, which leads to anticipatory control, can also be gained to a certain extent through observation. For example, many practicing neuropsychologists attend a human brain dissection workshop. Before participating in the actual dissection, the participant watches videos of an expert dissecting a brain, using blunt end and scalpel instruments or "tools." This observation has lead to the development of semantic knowledge (learning about blunt end and scalpel tools) as well as procedural knowledge which guides the participant's dissection, or movement, during the actual "hands on" activity, which is now embedded in the cognitive control system, or the control of action. However, the observation of the dissection generated the anticipation of what to expect in the actual performance of the dissection. In this way, observation generated anticipatory control over behavior. This "dissection" example is of particular importance in demonstrating how anticipatory thinking can develop through the observation of others, a point which will be discussed in a subsequent section of this paper. In other words, learning how to think, which controls what we do, can to a certain extent be acquired through observation. This is a critical underpinning for understanding how people who were never able to move can nevertheless learn to think. Observations can include learning about the intentions of others, which is one of the requirements of social interactions.

A final example is related to this interpersonal issue. Consider Pezzulo's description of an interior decorator. In this occupation, the designer can compare, in his or her "head," a variety of different furniture arrangements and color schemes in a room. This is cognitive control because it represents the thought manipulation of planning and anticipation. However, the designer will also anticipate, or predict, whether or not the customer will be satisfied. Or how much will the customer "like" the final product. In other words, what will be the level or degree of reward value? This subtle addition is critical because it includes a social, or interpersonal element. The interior decorator is actually imagining how the client will feel about the product or outcome; the designer is predicting the customer's reward preferences in order to "control" the action of designing the room. The decorator is essentially placing an anticipatory wager, or bet, on whether or not the client will like the furniture and color schemes. This example is critical because it illustrates the link between thinking (the off-line imagination of comparing furniture arrangements), the eventual generation of the outcome or product (the transformation of thinking to movement or action), and empathy, all of which are crucial aspects of adaptation, including social cognition. The interior designer is preparing or "readying" a response to an interpersonal event that has yet to occur. Therefore, both thinking and empathy are derived from the development of control over the motor system. Just as we anticipate or "place bets" on outcomes of activity, we also anticipate or place a "wager" on how another person will feel because of what we say or do. These processes of "simulation" and "emulation" are a fundamental integrating principle for cognitive control [200].

It is particularly obvious that the first two examples explicitly involved learning information and activities. In the final example, learning was more implicit. However, these examples warrant a "second look" to illustrate another principle. The individual who became an automobile mechanic, and the neuropsychologist who attended the dissection workshop, both explicitly wanted to learn not only declarative, but also procedural information, even though it is unlikely they conceptualized learning in these ways. At first, learning the new information was, by definition, unfamiliar. With repeated "practice," the mechanic student became an "expert," and much of what he learned presumably became "automatic" behavior. With repeated dissection practice, it is possible that the neuropsychologist who attended the workshop could become an expert at dissecting the human brain. However, without question, a staff "expert" who might have assisted the neuropsychologist in dissection very likely possessed automated dissection skills. In fact, the expert in the dissection video must have had automated dissection skills that were initially learned. So, embedded in these examples is the novelty-routinization principle of hemispheric behavioral organization. Extending this principle to include the typically developing child, this principle of brain organization is continuous and ongoing. Children have to learn how to perform a very wide variety of activities. These activities, such as personal hygiene behavior, dressing and undressing, using cups, spoons, and forks, etc., are all initially novel; with repeated activity, these behaviors become routine or automatic. Therefore, the novelty-routinization principle is also embedded in pediatric development. Just as "ontogeny recapitulates phylogeny," ontogenetic development recapitulates the novelty-routinization principle of hemispheric organization. This further emphasizes the critical importance of movement for the development of cognition. Procedural learning, or the acquisition of skill sets, is a driver of pediatric development. Failure to acquire motor and cognitive procedures, and difficulties in adapting them across similar situations, are characteristic of numerous neurodevelopmental disorders [183]. These failures predict future cognitive control difficulties as described above, and therefore have long-term outcome implications. The acquisition of procedures and habits, or routine behaviors, allows for the development of the cognitive control system and illustrates that automated behaviors and thinking must co-exist. When difficulties or slowness in acquiring personal routines is evident in a child's developmental history, these issues should never, ever be minimized or overlooked. Learned, automated behaviors are fundamental for independent living and autonomous functioning. And, in terms of the lateralization of some of these aspects of movement and cognitive control, the left hemisphere specializes for predictive control in order to plan and coordinate motor actions, while the right hemisphere updates and adapts ongoing actions while also mediating intention programs, including stopping and inhibiting [201]. These types of behaviors adhere to known lateralization patterns and follow the fundamental novelty-routinization principle of brain organization.

The Four Steps of the Development of the Cognitive Control System

Thinking evolved in order to develop the ability for anticipation to guide the physical actions necessary for survival. In other words, we "think" in order to control and anticipate the outcomes of what we do; we "think" to control the motor system; we did not develop the ability to think for the primary purpose of thinking per se. Four steps describe the development of this cognitive control system. Motor activity, and control over it, comes first. It is fundamental to survival, development and adaptation. Second, movement and cognition are coincidental. This is evident in the exploratory behavior of the toddler. A child learns about the world by discovering objects in the environment and learning about how to use them. The "value" of these objects represents reward characteristics. All of the properties of objects are learned by interacting with them. So in a way, this interactive "learning" occurs by coincidence. Third, motor activity and cognition co-exist. Through this interactive learning process, children start to form simple "intentions" about what they want and what they want to do because they learned about reward contingencies and they use that anticipatory cognition to "control" behavior. At this point, movement and cognition are inexorably linked, so there is no "duality" between movement and cognition. At this early stage in development, behavior is highly dependent upon "reward," and this is supported by the developmental anatomical trajectory of large scale brain systems. Fourth, these initial activities and cognitions become routine, such as feeding and playing. At this the time, the behaviors that were learned are automatic. Movement, or activity, then rises above cognition. These behaviors become routine, and conscious cognitive awareness and explicit control are no longer necessary for those behaviors. Cognition then resides a notch below automatic behavior. This four stage process repeats itself, over and over again, throughout the course of ontogeny. In fact, this summarizes the novelty-routinization principle that is evident throughout the lifespan.

We "step-down" and revert back to "cognition" in learning new activities and in solving problems. This often involves the abstraction of divergent thinking. We "imagine/predict/anticipate," how objects might be used in a way which is different from the way the object was initially intended, and we combine these

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"predictions" about different objects to meet the stimulus-based properties of problems for which there is no readily available or "routine" solution. We then use this information, derived from the "off-line" simulation of object use (thinking or imagining), to continue to guide the motor system. This is exactly why symbolic or imaginative play is so important in young children. It represents an early manifestation of the development of the cognitive control system. This is also why the absence of this type of play is often predictive of the development of disorders characterized by poor interpersonal skills or a lack of empathy. Adaptive interpersonal skills, and empathy, are not much more than anticipating what another person will think or feel on the basis of what we say or do, and we use that anticipation to control our behavior when interacting with others. In fact, Vakalopoulos, in a very comprehensive and detailed, compelling review, described how empathy develops from the motor system [202].

Abolishing the Executive and the Mind-Body Problem

Cognition is not separate from sensorimotor control; there is no duality between motor and "cognitive" functions. This was clearly implied in the examples of the automobile mechanic, the brain dissection workshop, and the interior decorator. Duality between these functions and processes is an artificial construct based upon philosophical assumption and/or the construction of artificial "domains." This dichotomy generates confusion, constraining our investigations for understanding the concept of cognitive control. Very simply put, there is no philosophical mind-body problem. It is well accepted within current neuroscience that all functioning, whether it is cognitive, emotional, or social, etc., is based upon the control, or lack thereof, provided by anticipation, and in particular, the anticipation of reward outcomes (see [203] for a comprehensive review). These reward outcomes, which are at the essence of adaptation, are at the heart of behavioral control. For the vertebrate brain, *the primary substantive difference between planning an activity and executing its motor counterpart is the actual execution of that behavior* [42, 110, 204–206]. In fact, imagery and actual movement share a common neural substrate. Mental rehearsal or imagining an activity improves performance [207]. Similar if not the same brain regions are recruited and activated during the performance of an activity and when imagining doing it [208]. The specific, multiple inhibitory processes that are involved in the difference between imagining an activity and the actual execution of that behavior have been investigated as well [209]. These critical issues will be revisited in discussing the cognition of people who are unable to move and the "thinking" of those who are either congenitally blind or deaf. In any event, the reality of constant environmental interaction, movement, and "thinking" is evident throughout the phylogenetic scale with reference to the vertebrate brain; it is biologically consistent for every vertebrate species. Human cognition might be different from animal cognition, primarily because we possess enhanced sensory capacities and can communicate through language, but human cognition and thinking are certainly not "special." The "bottom line" is the *anticipation inherent in movement control and interaction. This anticipation is always associated with some type of reward outcome*. Philosophical thinking which contemplates solutions to problems

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such as reasons for existence can never reach conclusions because the human brain was not designed for that type of thought capacity. Philosophical thinking lies beyond the parameters of the cognitive control system because once again, cognition was derived from the motor system in order to control it. Philosophical thinking has no motor outcome. We only engage in this type of thinking because anticipation is inherent in the fundamental design of vertically organized brain systems. Thinking becomes increasingly abstract in philosophical contemplation, but it never generates a concrete result because it has no identifiable reward outcome based upon sensorimotor activity. That conclusion might sound too simple, so simple that it is unbelievable. That is exactly why Winston Churchill was quoted in the opening of this volume—"Out of intense complexities intense simplicities emerge." With these types of complicated problems that seem too formidable to solve, it can make good sense to ask questions that lead to stimulus-based controls.

Why Cognitive Control Is an Expansion of Cortical-Cerebellar and Cortical-Basal Ganglia Motor Control Systems

In addition to the lateral left and right hemispheric divisions of the brain, the neocortex can also be divided along an anterior and posterior gradient. The posterior regions, or the occipital, parietal, and temporal lobes, can be thought of as elegant sensory processors. The hippocampal memory system, which supports semantic and episodic memory, primarily allows sensory-perceptual experience to persist. This is essentially a recognition memory system that binds sensory experiences processed by distributed brain networks, allowing this information to be retained or remembered. This memory formation system is tucked inside the medial temporal lobes [210]. The divisions of the frontal lobes reside anterior to the central sulcus. The frontal lobes can be thought of as exquisite motor or activity programmers. Through the sequencing and binding operations of frontal-striatal interactions, procedural memories, or motor programs, are stored or retained within supplementary and premotor cortices. The operations of the visual, ventral and dorsal attention networks reside within posterior regions, while the integrated operations of the dorsal attention and sensorimotor networks, and particularly the parietal lobes, specify the parameters for frontal system motor programming and activity. Learning new motor programs, or activities, is dependent upon direct sensory feedback, so that the interactive "problem-solving" activities of the neocortex are believed to function slowly [158].

Interacting with the world in "real time" requires quick responding. The cerebellum serves the function of "by-passing" direct, slowly operating sensory feedback, which allows for behavior to be automated and adapted across contexts. In other words, the cerebellum eliminates the need for direct sensory feedback on the basis of learning to predict, or anticipate motor outcomes after repeated practice of behaviors. Therefore, the frontal-cerebellar system functions as an anticipatory control mechanism. This system is the neuroanatomic underpinning for anticipatory cognitive, neocortical control.

The basal ganglia is essentially an instrumental learning mechanism. It learns, or operates, on the basis of reward value. It is a motor, cognitive, and motivational "gating center" that selects behavior on the basis of reward outcomes. It serves this

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function by selecting activities that have achieved positive outcomes and that have avoided negative outcomes. The frontal-basal ganglia system therefore serves the role of contributing to cognitive control by providing the "reward value" component for the frontal-cerebellar anticipatory system. Therefore, the evolution of the cognitive control system required the expansion of the functions of both cerebellar and basal ganglia operations. These two vertically organized brain systems were reviewed in Volume I [2], and the following sections expand upon the operations that were previously described.

The Cerebro-Cerebellar Underpinning of Cognitive Control

During the course of evolution, the neocortex demonstrated a significant expansion. This increase in size actually reflects increased specialization. It is not really "size" that matters. Instead, within this expanded area, there are new sensorimotor systems. The increased capacities for processing different types of sensory information and experiences and the increased abilities to develop more complicated compound movements required the evolution of highly specialized neurons, which resulted in a dramatic increase in neocortical size [165].

However, Smaers and colleagues examined the cortico-cerebellar system in 19 anthropoid species spanning across 35 million years of divergent evolution, and this review generated the compelling conclusion that the neural systems involving cortico-cerebellar reciprocal connections were a major factor in the evolution of anthropoid brain organization [150, 211]. In humans, every region of the neocortex (with the exception of the inferotemporal cortex) has reciprocal, segregated, non-overlapping connections with the cerebellum (for a primary source review, see [38]). The cerebellum has demonstrated a parallel developmental pattern that corresponds with neocortical expansion; there has been a three- to fourfold expansion in humans compared to other species [212]. Along with this expansion, the dentate nucleus of the cerebellum has significantly increased in size; reciprocal connections between the prefrontal cortex and the dentate nucleus have been identified in humans that are not present in other species [151, 213, 214]. In this regard, "size" is not the critical feature for cerebellar expansion either. What matters is the neuroanatomic fact that reciprocal connections between the prefrontal cortex and the cerebellum/dentate nucleus have been identified in humans that are not present in other primates. The identification of these connections presents compelling neuroanatomic evidence for a cerebellar role in a variety of functions, including attention, learning and memory, and in short, all functions relevant to the cognitive control of behavior [215–217]. In an extremely compelling investigation, it has been concluded that certain prefrontal projection regions of the cerebro-cerebellar circuitry profile process information that is of a purely abstract nature [186, 218]. The expansion of the neocortex is of critical importance, but neocortical developments were

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accompanied by a parallel expansion of the cerebro-cerebellar circuitry system. In other words, the argument presented has a firm, unequivocal underpinning in neuroanatomic "fact." This coordinated expansion of the neocortex and cerebellum is considered the neuroanatomic substrate for these regions functioning as an ensemble or network [219].

Structure and Function of the Cerebro-Cerebellar Circuitry System

Schmahmann and Pandya [38] are arguably the primary source in describing the cerebro-cerebellar circuitry system, although other investigators have made critical contributions as well [215, 218]. While it is assumed the reader is familiar with this material, a brief, simplistic summary with a review of basic principles, is nevertheless provided. Cerebro-cerebellar circuits originate in the cerebral cortex; from the cortex, they project to the pons; from the pons, circuits project to the cerebellar cortex through the mossy fiber system; information transmitted within these circuits is modified by passing through the infrastructure of the cerebellum; circuits then project to the deep cerebellar nuclei, while the dentate nucleus primarily receives projections that originated from the neocortex; from the dentate nucleus, circuits project to the thalamus, and from there, back to the point of origin in the cerebral cortex. There is also an Olivary system which connects the inferior olive to various regions of the cerebellum. All circuits are segregated, or independent from each other; for a detailed review of the functions of the infrastructure of the cerebellum, see Ito [158]. The cerebro-cerebellar circuitry profile was previously illustrated in Volume I [2].

So, what processes occur within this ensemble? It is well known that direct cortical sensory feedback processes operate slowly—much too slowly for us to generate behavior in "real time" [160, 161]. In learning a behavior, the perception and processing of sensory feedback, translating that sensory information to modify or correct a behavior as we learn it, and then transmitting that information to the musculature for motor execution is time consuming. The cerebellum and its circuitry systems essentially function as a *predictor or anticipator*.

Cerebellar brain mechanisms have evolved that allow the organism to predict or anticipate sensorimotor feedback in order to generate rapid, automatic, adaptive behaviors. These mechanisms are referred to as internal models [158, 220]. The development of these models is made possible through the 'mossy fiber' cerebro-cerebellar circuitry system. This system essentially allows the cerebellum to copy the contents of cortical "working memory," or what the brain intends to do, which is essentially the construction of the cerebellar control model.

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A cerebellar internal model therefore consists of all of the dynamic sensory and motor processes that are necessary to perform a movement or behavior. This internal model is formed and refined each time a movement is repeated. The refinement occurs as a function of the cerebellar olivary system's detection of errors or imprecision in performance. It refines its prediction of feedback with each movement, and makes adjustments in the execution of each movement accordingly. As a result, the internal model enables the brain to execute the movement with increasing precision, without the need to refer to feedback from the moving body part. The cerebellum learns through repetition of operations to perform them faster and more accurately, which explains how a person is able to move with increasing skill after repeated practice [158].

A cerebellar model can be thought of as a predictor of the consequences or outcomes of motor commands, which allows the behavior to become increasingly precise and automatic and increasingly executed by processes that are out of conscious awareness. The cerebro-cerebellar circuitry system projects the most efficient behavior to motor regions of the cortex, which allows the cortex to store the most efficient representation of the behavior [113] and use this representation to inform the model that drives the behavior the next time it is executed. This circuitry system allows for a behavior to be adapted to a similar situation that is not exactly the same. In this regard, the cerebellar model predicts the sensory consequences of action [158]. Therefore, the operations of the cerebellum include the ability to *adapt behavior across similar contexts* [183].

The internal structure of the cerebellum is uniform. It is generally agreed that this means the cerebellum can perform only one uniform operation, although this operation or function can be considered from many seemingly diverse points of view [186, 204, 221]. The cerebellum is also modularly organized. Overlearned motor behaviors are represented by control models within the anterior lobes of the cerebellum [222]; learning new sensorimotor behaviors, and cognitions, are modulated by the posterior and inferior lobes of the cerebellum [162, 186, 223]. The cerebellum can be thought of as a "supervised learning system" [224] because of its error detection and correctional capabilities. However, the cerebellum can primarily be considered as an anticipatory control mechanism; it informs the cerebral cortex about the predicted outcome of movements. In this way, it allows the cerebral cortex to execute movements in "real time," outside of conscious awareness [225], via by-passing slowly operating cortical feedback. However, because the cerebellum performs only one operation, what it does for movement, it also does for thought [204]. Koziol and colleagues [2, 34, 109, 110, 186, 190], and in Volume I [2], it was proposed the cerebellum instructs the prefrontal cortex about thought outcomes; it "teaches" the prefrontal cortices to anticipate or think ahead, and to anticipate what the outcome will be if a thought, or series of thoughts, is translated into behavior. In this way, it also allows for thinking in "real time," outside of conscious awareness. Therefore, the cerebro-cerebellar system is a critical underpinning of thinking and anticipatory cognitive control [220]. And, just as the most efficient representation of a motor sequence is stored within motor and premotor cortices [113], the most efficient representations of thought sequences are likely represented in more anterior frontal cortices. In other words, the cerebral cortex retains what the cerebellum learns. Just as the premortor cortex retains the most efficient representations of sequences of movement, more anterior, and prefrontal cortices likely represent the most efficient representations of thought sequences [186]. This contributes to implicit thought processes, since the operations of the cerebellum are believed to occur outside of conscious awareness [225]. In fact, Thach has proposed that cerebellar activity can initiate movement, or purposeful activity, implicitly, outside of conscious awareness [226]. This viewpoint also supports the argument that considerable human activity is largely automatic and routine, a factor that clinical neuropsychology has never seriously considered as fundamental to cognitive control.

In any event, it is clear that cognitive information is represented within the cerebellum. Imamizu and colleagues demonstrated that a modularity exists in the lateral cerebellum for cognitive functions [222, 227, 228]. When applying fMRI to investigate cerebellar activity as subjects learned to use two novel tools, they demonstrated that lateral and posterior cerebellar activation for the two different tools was spatially segregated, since there was less than 10 % overlap between two adjacent cerebellar brain regions. The subjects were also able to easily switch between using these different tools. They interpreted the findings as reflecting a modular organization within the posterior, lateral cerebellum for two different cognitive functions, since learning to use these tools required different cognitive input. Higuchi, Imamizu, and Kawato evaluated activation within the cerebellum as subjects used 16 very common tools, assuming that the use of these tools was automatic, since they manipulated objects such as scissors and a hammer [228]. When these subjects were actually using or manipulating these tools, the anterior or motor regions of the cerebellum were activated. However, when only imagining or thinking about using these tools, the posterior cerebellum was activated. In addition, different regions of the inferior posterior cerebellum were activated for each tool. The findings were interpreted as demonstrating internal control models for tool use. The findings also implied that purposive cognitive information was modularly represented in specific regions of the cerebellum. Since the operations of the cerebellum are presumably not reflected in consciousness, the findings also imply that cognitive information can exist and be applied outside of conscious awareness [225]. Modular organization for activity and cognitive representations within the cerebellum is depicted in Fig. 1.

At this point, it is useful to refer back to the arithmetic computation example of 82–38. The declarative "content" of this problem consists of the numbers. This content could easily change to other numbers, such as 37–18, and the perception of these numbers would presumably be mediated through cortical perceptual processes and control. However, the solution or computation of these problems requires a *procedure*. This cognitive procedure can be represented in a cerebellar model, since the procedure is actually a controlled motor action that needs to be applied to any subtraction problem with a similar configuration of numbers. The cerebellum assists the brain in making this procedure *automatic* and in *adapting* the same procedure, the regrouping and carrying and borrowing of numbers, every time this type of configuration is recognized. As soon as the configuration is identified, the brain *anticipates or predicts* that this is

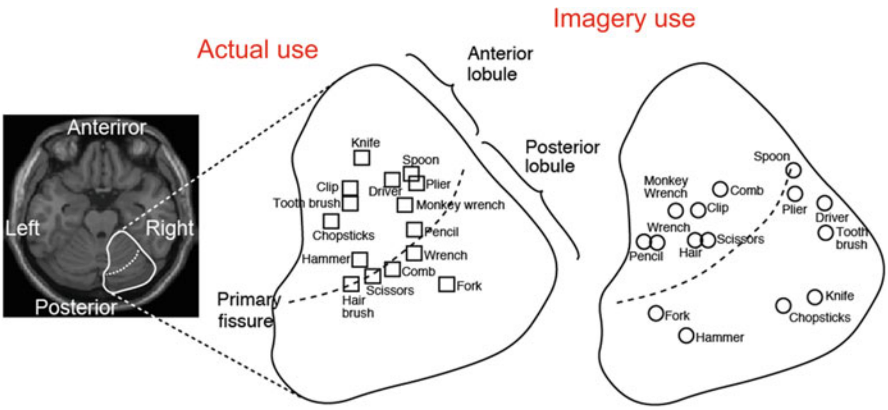

Fig. 1 Illustration of the modular organization for motor and cognitive functions

the required procedure for solving the problem. The brain immediately "knows," almost intuitively, without giving the matter a conscious thought, that if this procedure is applied, the correct answer to the subtraction will emerge. The brain predicts the *outcome* of the procedure. This same example can also be applied to Pezzulo's proposition that procedural knowledge results from interaction with the environment, and that reflecting upon the procedure can generate declarative knowledge. In this regard, the primary way this type of arithmetic computation can be acquired is by actually *doing it*; these types of problems are computed over and over again until the "sequence" is automated and retained. In simple terms, the acquisition of the procedure requires sensorimotor interaction with the computational problem. However, in imagining or in simulating what was done, we can now explain to another person how to solve those types of problems; our thinking about the procedure has led to acquiring information that can be told, or "declared," to another individual. This is certainly a form of cognitive control, while also demonstrating the relationship between movement (the procedure) to thinking (the declarative knowledge about the computational procedure). Similarly, this clearly has implications for understanding academic "learning disabilities," which, unfortunately, is beyond the scope of this paper's selective review [229, 230]. Finally, the recognition and application of the procedure is clearly an *abstraction*, consistent with the views of others that the cerebro-cerebellar ensemble plays a role in the abstraction inherent in problem-solving and divergent thinking [218, 231]. (Note: Neuroimaging studies demonstrate that in the computation of arithmetic problems, several different regions of the cortex are recruited, while the cerebellum is also activated; the specific role of the cerebellum in computation has not been systematically investigated as it has been for tool use. Generally speaking, the study of the functional neuroanatomy of mathematics is in its infancy. The example reviewed is based upon the prediction of a role for the cerebellum in computational arithmetic [232, 233]).

In previous papers, a more extensive, developmental example of how a child develops procedural and declarative knowledge, as well as the foundation for cognitive control through "tool use", was described [109, 110]. For instance, silverware use is essentially tool use; tool use is important because it represents an extension of the body's limbs and how an individual acquires this level of "action control." Using silverware, such as a fork, spoon, and knife is essentially a manifestation of an extension of the limb, in this case, the arm, hand, and fingers. Each one of these objects requires a different grasp; each object requires a somewhat different movement towards the mouth; each object is moved a bit differently while a different outcome is anticipated; since the mouth is not visible to the child, a cerebellar control model is likely constructed, just as a cerebellar model is necessary for the neurologist's finger-to-nose test; the silverware is moved towards to the mouth by *predicting or anticipating* its location; the process mimics the cerebellar-based "finger-to-nose" test that is part of a neurological examination. The use of silverware is not interchangeable; a fork cannot be substituted for a spoon. Different silverware are used for foods of different textures, or foods of different properties. Learning to use these tools, and reflecting upon or mentally simulating the activity, generates *procedural knowledge*. However, the *declarative knowledge* that can be generated can also lead to the development of semantic categories when learning about types of foods, their properties and textures such as liquids/soup versus meat, and even the semantic and more abstract fact that a knife can be used not only to cut meat, but it can be used away from the table as well, in the performance of other cutting activities. Even this common example should easily serve the purpose of demonstrating that a child's interactional activities can lead to learning an extremely wide variety of procedural and declarative information that contribute to cognitive control. Although the development of cerebellar control models has not been studied in children, the example is consistent with the conclusions derived from investigations with adults.

The Basal Ganglia Underpinning of Cognitive Control: The Fronto-Striatal System

The organization of the cortex includes widespread connections with the basal ganglia. The basal ganglia are a group of subcortical nuclei that are bilaterally represented within the brain. These nuclei consist of the striatum (a general term that includes the caudate, the putamen, and the ventral striatum/nucleus accumbens), the globus pallidus (which is divided into two separate compartments called the external and internal segments), and the subthalamic nucleus and substantia nigra (which can be further divided into the substantia nigra pars reticulata and the substantia nigra pars compacta). The striatum is divided and referred to by its dorsal and ventral components; the subdivisions of the globus pallidus are referred to as the Gpe and Gpi, according to its two compartments; the subthalamic nucleus is referred to as the STN, and the organization of the substantia nigra complex often follows the abbreviations SNr and SNpc. These are phylogenetically old regions of the vertebrate brain, these regions have very similar anatomic and neurochemical profiles across species, and they are believed to serve the same functions in all vertebrates [234–237]. In fact, the structure and function of the basal ganglia have been conserved over some 560 million years of evolution [238]. Therefore, the argument concerning the role of the basal ganglia presented in this paper certainly has a compelling history on its side. You simply cannot have a vertebrate brain without the basal ganglia. (This paper assumes the reader has a fundamental knowledge of the basal ganglia; reviews are provided by [1, 46, 239, 240]; the following information provides only a minimal, elementary summary of basal ganglia structure and function).

The cortex and the basal ganglia are connected through four pathways. The prototypical circuits are characterized by two connectional profiles; activity within the direct pathway releases a behavior, and activation of the indirect pathway stops that behavior. There is also a hyperdirect pathway that connects the frontal cortex to the STN; activity of this pathway generates global inhibition, stopping behavior, obviously important in situations where it is necessary to plan and organize new responses. A fourth striosomal pathway projects from cortically-based paralimbic regions to the SN complex, which provides the basal ganglia with information about

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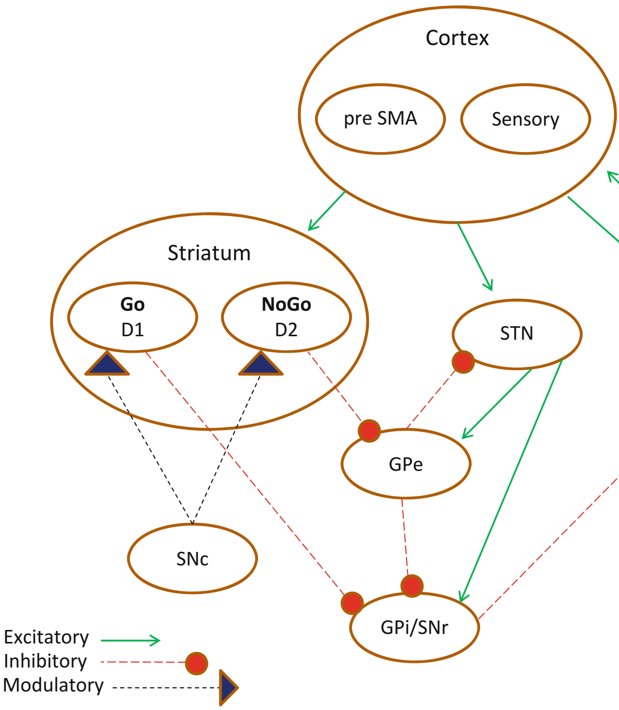

Fig. 1 Simplified illustration of the BG circuit

the reward value of particular contexts. A functional illustration of the basal ganglia is presented in Fig. 1 (Also, see Volume I of this series [2]).

Alexander, DeLong, and Strick initially identified the five prototypical frontal-striatal (basal ganglia) circuits, and their seminal work has arguably become the most quoted paper in contemporary neuroscience because of the impact cortico-striatal circuitry has had upon the understanding of brain-behavior relationships [37]. Middleton and Strick later added two prototypical sensory-perceptual circuits reciprocally connecting the temporal and parietal lobes with the basal ganglia system [214]. (See Volume I of this series for an explanation and illustration of how these circuits relate to large scale brain networks [2].) All of these circuits are topographically organized, segregated, and function as parallel processes, so that to understand the operational mechanisms of one circuit allows for an understanding of all connectivity profiles. How to translate motor behavior to cognitive, motivational, and affective analogues has previously been described by Koziol and Budding [1]. In a meta-analytic review of fMRI studies, Arsalidou and colleagues generated a comprehensive "topographical map" of how body and eye movements, cognitive functions, emotional and reward processes, and somatosensory functions are regionally represented within the basal ganglia [241]. The segregated operations of these circuitry profiles explain how attention and action/behavioral selection become highly focused and maintained. There are four additional integrative networks of the basal ganglia which explain how information flows between circuits which is necessary for modifying previously learned behaviors and for the development, acquisition, and implementation of new behaviors [199, 242–244].

The basal ganglia are key players in modulating a wide range of functions and behaviors. These functions include various types of category learning [4, 6, 44, 157, 245–247]; the learning of new motor behaviors and sequences [248, 249]; the rule-governed support for grammar systems [139]; the selection and gating of focused behaviors [237]; the cognitive control of explicit working memory tasks [42, 43, 122]; instrumental learning processes [184]. All of these functions reside within the broad definition of cognitive control processes. Because of this extremely wide range of functions, it can be very tempting to infer that the basal ganglia subsume multiple, diverse roles while even operating in multiple different ways. However, this is a misleading conclusion. When "following the yellow brick road" of a neuroanatomic perspective, the basal ganglia can be considered as a sort of central relay station because this is where projections or inputs from numerous cortical (and brainstem) structures and regions converge. For purposes relevant to this discussion, these regions include the prefrontal cortex, motor cortices, sensory cortices, as well as the amygdala (which lies at the tip of the tail of the caudate) and the hippocampus. This places the basal ganglia in a unique position to integrate information from multiple brain systems and large scale brain networks. This anatomy is the underpinning for all "candidate" cognitive and motor actions represented or stored within the frontal cortex. These "candidates" can be described as potential choices or decisions. Through the process of selective disinhibition and inhibition of thalamic nuclei, the basal ganglia "gate" or release the most adaptive of these "candidate" actions to be executed, while suppressing all other competing actions. Therefore, the basal ganglia can currently be best understood as serving a unified, integrative role [250]. The basal ganglia are an inhibitory system that dynamically and adaptively selects or "gates" the flow of information through its cortical-striatal-pallidal-thalamic-cortical loops [28]. However, how do the basal ganglia "know" which "candidate behaviors/cognitions" should be facilitated or released, and which should be inhibited or suppressed? The answer to this question is critical to understanding the neuropsychology of cognitive control, and the clue to this answer is found by considering the basal ganglia as a reward based, reinforcement or instrumental learning system.

Cognitive Control, Reward, and the Basal Ganglia

The action selection, or gating function of the basal ganglia is dependent upon the integrity of the dopaminergic reward system (see Volume I for an illustration of dopaminergic pathways [2]). At base, this is essentially a reinforcement or instrumental learning system that works in the following fashion. Whenever a "stimulus" is represented (either imagined or concretely perceived) within the sensory cortices, this generates "candidate actions" or "behavioral choices" within the premotor cortex; this occurs because (as indicated in a section above that described the ventral and dorsal brain networks), all of the essential properties of "objects" are represented in the same sensory and motor brain circuits that were recruited or activated when the information about those objects was initially acquired. These sensory and premotor cortical regions project to the striatum, through the direct and indirect pathways.

The direct pathway (characterized primarily by D 1 receptor activity) provides very focal, inhibitory input to the topographically organized GPi; in the absence of cortical-striatal input, the GPi is tonically active; continuous, spontaneous activity projecting to the thalamus is the "default mode" of the GPi. This GPi activity is entirely characterized by inhibitory projections to the thalamus; this tonic activity prevents the thalamus from facilitating or releasing any and all cortical response representations. Therefore, the GPi essentially functions as a "brake" on the thalamus, preventing cortical "candidate actions" from being expressed. However, when the D 1 neurons of the direct pathway are activated or "fire," this inhibits or stops the GPi from inhibiting the thalamus. Because removal of this GPi inhibition over the thalamus is very focal, only a specific "candidate behavior" is facilitated; the topographically organized and highly compartmentalized thalamus amplifies the representations of only a specific candidate behavior; all other potential candidate actions, or behavioral choices, are suppressed or remain inhibited. Frank refers to the activity of the direct pathway as a "Go" signal [43, 184, 251].

Within this model, the "decision making" that disinhibits the thalamus and generates a behavior requires "top down" signaling or excitation from the cortex. Orbitofrontal representations of expected or anticipated reward value are

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presumably involved in decision making dependent upon higher-order cognitive control, including input from the FPN [179]. However, once a behavior is learned and represented within the premotor cortex, the proper contextual stimulus can release that behavior outside of conscious awareness. In other words, an appropriate stimulus within the appropriate context can release the behavior, as in the execution of behavioral routines that we all engage in on a regular basis. In any event, within this model, "top down" decision making requires "bottom up" (basal ganglia) support. This again reflects the conclusion that the cognitive control system is an evolutionary expansion of the frontal-basal ganglia network.

The indirect pathway is characterized by the expression of D 2 receptor activity. This pathway can be thought of as operating in opposition to the direct pathway. The indirect pathway features inhibitory connections of the striatum to the GPe; the GPe has inhibitory connections to the STN, while the STN has excitatory connections to the GPi. Therefore, activity within the indirect pathway (which is associated with decline in dopaminergic transmission), actually causes the STN to increase the tonic inhibitory activity of the GPi, which suppresses behavior.

Activity within the direct pathway always leads to positive reinforcement, associations, and the performance of the behavior in question; this is associated with "bursts" or increases in dopaminergic activity. Activity within the indirect pathway always leads to negative outcomes and the avoidance of those behaviors; this is associated with "dips" or decreases in dopaminergic activity. The neural systems governing these behaviors that are strongly and repeatedly coactivated are strengthened. According to stimulus context and generalizability, the basal ganglia release those actions that have a high probability of generating a positive outcome; they avoid selecting actions that have been associated with negative outcomes. So the frontal-striatal system learns what to do as well as what it should not do, which of course, depends upon the stimulus context in question and its reward properties [250].

A general anatomic pattern of reward based reinforcement learning and procedural learning can be identified. Generally speaking, there is a dynamic shift from cognitive and sensory corticostriatal "loops" to the motor loop across the time course of learning, in other words, as the individual benefits from the experience of interacting with the environment [157]. This dynamic activity has been described as representing a transfer of information within patterns of interaction between these corticostriatal loops. The typical pattern features a marked gradient from ventral, anterior, and medial regions of frontostriatal circuits out to the most superior, posterior, and lateral regions. In other words, brain activation proceeds from the dorsal and ventral striatum out to the putamen, with sensory loops lying in the middle of the gradient. Motor skill learning dynamically shifts from the cognitive control loop to the motor loop. This pattern presumably reflects the FPN's involvement in the initial higher-order control required for acquisition of the task and the motor loop being involved in task execution and automaticity [103, 252]. This learning process is illustrated in Fig. 1.

Of primary, critical interest here concerns the proposal that traditional concepts of EF, which includes the fractionalization of EF into sub-domains such as "working memory," "inhibition," and "planning" cannot possibly be distinct, "all or none,"

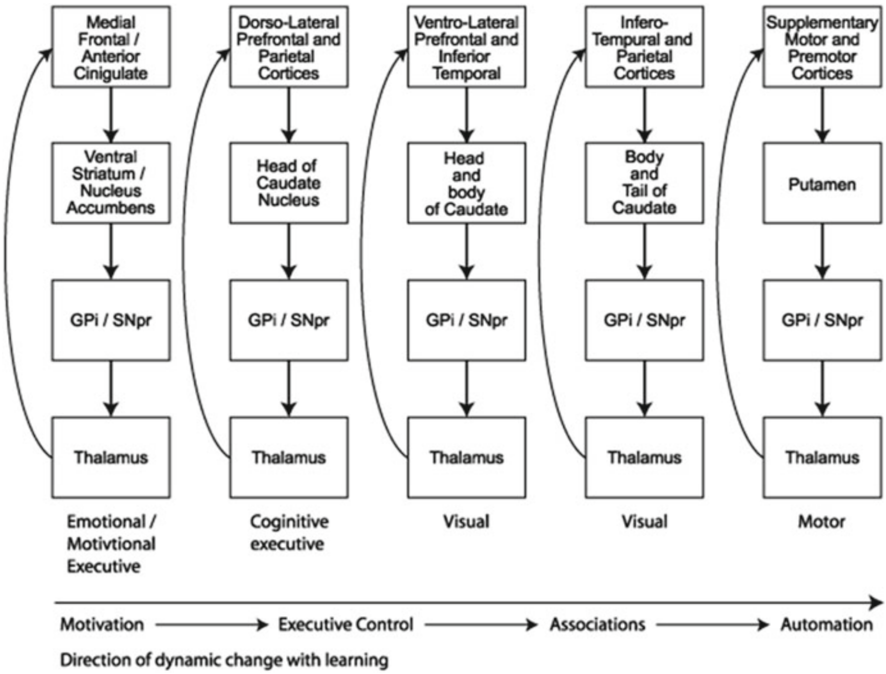

Fig. 1 Diagram of the dynamically changing neuroanatomy of the learning of an activity

unitary entities. These fractionated domains have only served the purpose of constraining our understanding of EF. For example, by definition, the learning of new tasks and procedures that require the FPN guidance of "working memory" are clearly task dependent [22, 23, 35, 95, 128, 253]. As these tasks and procedures are acquired, the neuroanatomic underpinnings shift from "executive control" to automaticity, with increasingly less dependence upon the cognitive control of "working memory" guidance. Current neuropsychological tests assess "working memory" as a static, explicit entity; within a neuroscientific framework, working memory is a dynamic, task dependent phenomenon. There is no "central executive." The "executive" is really the brain network, or networks, that are recruited by any given task. The brain networks are dynamically changing according to the specific task or tasks being performed, particularly since we are always engaged in interactive behavior. Therefore, the "executive" can never be "assessed" by anything other than the specific task itself used to assess it [42, 43]. There is a cognitive control system, characterized by a changing pattern of brain network activation, but there is absolutely no need for a general construct of "EF." This is exactly why tests of "EF" such as card sorting tasks, various "tower" problem-solving tests, and different "working memory" tests do not correlate very well with each other, and why performances on these types of tests do not predict "EF" efficiency in executing the tasks of daily living. These tests, and the various practical tasks of independent, autonomous daily living, reflect the operations of cognitive control systems and the recruitment of the operations of various brain networks. In order for clinical neuropsychological assessment to effectively evaluate the cognitive control system, a "paradigm shift" is critically necessary. This includes dropping all assumptions about "EF" and its possible subcomponents. This new assessment paradigm needs to conceptualize cognitive control as a *dynamically changing* neuroanatomy that supports interactive learning which is grounded in the concepts of anticipation and reward. The "executive homunculus" of the prevailing "EF" model needs to be abolished in favor of assessing neurodynamic processes [128, 250].

Basal Ganglia Dynamics, Cognition, and Social Behavior

The basal ganglia gate cognition the same way they select behavior, on the basis of activity within the direct and indirect pathways. For example, within the FPN, and the general cognitive control system, the temporary storage of information to guide behavior is supported by prefrontal-parietal circuitry [254]. Cortical-basal ganglia interactions through the direct and indirect pathways literally “let in” task relevant information while “keeping out” distracting information which allows for appropriate information maintenance, manipulation, and updating [42, 43, 122, 123, 205].

The critical “key” to understanding the basic unifying, integrative role of the basal ganglia system in all of these seemingly divergent functions concerns the conceptualization of “**reward**.” The dopaminergic reward system is essentially governed by the ventral striatum/nucleus accumbens. Activity in this region clearly increases in response to food, water, and sexual activity, often referred to as primary reward and/or consummatory reward [242, 255]. However, this reward system region is also activated in response to secondary rewards such as money, praise, and other signals of social status [256]. The brain’s “reward signal” appears to be more accurately modeled and characterized hierarchically, as a series of multiple processes which are associated with various levels of abstraction [46]. Reward representations do not have to be concrete, direct indications of reward. Instead, these reward representations can be cognitively and abstractly or imaginatively mediated. For example, reward related activity occurs in response to the achievement or accomplishment of an unrewarded goal, such as completion of an academic task or the completion of this ebook; similarly, the reward center can be recruited in response to a possible, imagined reward that is not actually tangibly experienced, a concept originally referred to as “fictive reward” [257]. The ventral striatum and ventromedial prefrontal cortex demonstrate changes in activity levels in response to changing rewards. For example, common activations in these regions are observed with concrete monetary reward, in cooperating with other people, in conforming to the opinions of experts, in positive/negative comments from other people, and even in making altruistic charitable donations [258]. Therefore, an extremely wide variety of types of “reward” are the critical underpinning that allow the basal ganglia to mediate activity encompassing a

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very broad range of situations in which "learning" how to interact with the environment is important. Knowing about this "clue" to understanding the basal ganglia's instrumental learning processes is another example of how evolution has developed "new" functions and behaviors by building upon existing functional systems, while maintaining the co-existence of multiple systems, many of which can inhibit or over-ride prepotent responses. For example, in achieving the "unrewarded goal" of completing this manuscript, many much more inherently rewarding behaviors were necessarily inhibited. Motivation, reward, anticipation, and the ability to benefit from the experience of interacting with the environment are critical to understanding the neuropsychology of the cognitive control system. This generates a compelling argument for including tests of procedural learning and assessing reward preferences in neuropsychological evaluations. Instead of continuing to maintain false, misdirected assumptions, the likely possibility that all aspects of these systems, processes, and functions can be comprehensively "tested" must be entertained. However, various functions can certainly be "sampled."

Interim Summary

This paper recommends banishing the term "executive functioning" and replacing it with the concept of a "cognitive control system." This system is likely an evolutionary extension of the vertically organized cerebro-cerebellar and cortico-basal ganglia motor systems. The case for replacing the term "EF" was presented within a problem-solving paradigm. It was emphasized that continuous interaction with the environment, throughout the course of evolution and human development, generated a cognitive control system which is based upon anticipation and reward. The learning of procedures, the acquisition of aspects of declarative knowledge, and information about reward value are acquired through this ongoing interaction. It was stated that anticipation is a fundamental design characteristic of the brain, and that this was evident in both movement and thinking. It was proposed that thinking evolved for the specific purpose of controlling and guiding the motor system in order to adaptively interact with an environment that became increasingly complex throughout the course of phylogeny. In this regard, cognition is not separate from sensorimotor control. Thinking is directly linked to motor activity. The only difference between thinking and activity is the actual execution of the behavior.

The vertebrate brain is organized according to a novelty-routinization principle. It learns new behaviors and gradually makes them automatic/implicit as they are repeated in order to exploit the predictable, routine features of the environment. This conserves biological resources. The learning of a new activity is initially dependent upon slowly operating neocortical sensorimotor feedback systems in order to judge their efficiency. In order to by-pass this process and achieve efficient automaticity, the cerebellum developed anticipatory control models to predict sensorimotor outcomes. With repetition, the cerebellum learns the most efficient neural representation of the behavior, while the motor cortex then retains what the cerebellum learns. Throughout the course of phylogeny, this anticipatory process expanded in order to teach the neocortex the most efficient representations of thought patterns and sequences, in order to anticipate thought outcomes. The basal ganglia select and inhibit behaviors on the basis of instrumental reward outcomes. During phylogenetic development, this expanded to include a hierarchically

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organized reward system in order to associate rewards with increasingly complex behaviors and increasingly abstract, anticipated thought outcomes. In this way, the cognitive control system represents a merging of the cerebro-cerebellar and cortical-basal ganglia systems. However, there is no "executive" because ideas, choices, decisions, and thought manipulation are represented over large regions of the cerebral cortex and expressed in both the explicit and implicit operations of large scale brain systems. Within this behavioral management system, the locus of control is constantly changing on the basis of the level of task acquisition, reward probabilities, and environmental demands. The cognitive control system developed to meet the needs of interactive behavior. Within this system, automaticity of behavior and cognitive control must co-exist. This represents the evolutionary fact that nature's oldest solutions for generating adaptive behaviors do not involve or emphasize sophisticated cognition or conscious cognitive control. This evolutionary phenomenon was very strongly conserved throughout the course of phylogeny. Much of human adaptation is characterized by routine, automatic behavior, so that higher-order cognitive control processes are engaged relatively infrequently.

How Well Do These Principles "Fit" Exceptional Cases?

So, if the attentive reader follows the logic of this argument, a seemingly significant problem emerges. Why is it that people who were never able to move still acquire thinking capability? Once again, consistent with the theme of the previous presentation, there must be "clues" for determining the stimulus-based characteristics of this issue in order to answer this seemingly perplexing question. And, once again, the answer might be deceptively simple, since "out of intense complexities intense simplicities emerge."

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Why People Who Cannot Move Are Able to Think

The first clue in approaching an answer concerns the fact that for the brain, the only difference between planning or imagining an activity and engaging in the activity is the actual execution of that behavior. It is well documented that very similar, if not identical brain areas are recruited during the process of thinking about an activity and when actually performing that behavior [207, 208]. The primary difference is the activation of the motor system when that behavior is executed. The second clue concerns the fact that it is also well documented that mentally rehearsing, or imagining the execution of a behavior, actually improves performance [207, 208]. For example, in one study, it was concluded that viewing tools seemed to generate prehensions and anticipations about using them; the imagined action of using a tool "mirrored" the brain activation underlying the functional use of the tool [259]. The perception of the tool, the contextual coupling of the action of using the tool, and the imagination of the activity generated the precursors or forerunners of overt "action control" over tool use. In addition, it has been documented that the planning of the use of a tool activates or recruits a distributed large scale brain network within the left hemisphere. This network includes the posterior superior temporal sulcus, a brain region necessary for the perception of motion; proximal regions of the middle and superior temporal gyri were also recruited, which are brain regions associated with the memory of the identification of objects and the assignment of appropriate context for objects, in other words, salience assignment; the anterior and posterior supramarginal gyri of parietal regions were recruited, which are brain regions that are necessary for specifying the parameters of action, insofar as grasp of the tool might be determined by its size, shape, and movement; the inferior frontal and ventral premotor cortices were activated, as well as the dorsolateral prefrontal cortex, regions necessary for the execution of movement and for decision making over action. These regions have been described as an "action control" network [2, 75, 110, 260], while it also should be noted that these brain regions include what some investigators have termed the "mirror neuron system" [158, 261, 262]. While activity within the left DLPFC dropped out during action execution (which makes sense after the decision to act was made to choose that particular candidate behavior),

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adjacent and partially overlapping areas of the left temporal, parietal, and frontal cortex were engaged during action execution. As cited above, when the cerebellum was included as a brain region of interest (ROI), differential regions of the anterior and posterior inferior cerebellum were also activated during actual and imagined tool use. The data identify the lateralized large scale brain network referred to in this and earlier papers as a functional ensemble for the interaction of semantic/declarative and motor/procedural representations upon which meaningful skills depend [263]. Therefore, while in reviewing Pezzulo [116–118] it was concluded that procedural knowledge can lead to the development of declarative knowledge, the opposite relationship is similarly evident. Declarative knowledge can facilitate procedural learning through the process of *observation*. This was similarly evident in the prior example of attending a brain dissection workshop.

So, let us imagine that you wanted to learn how to use a new tool; assume that the only experience you had about using that tool was derived from observation and mental imagery. You would already know how to use that tool. You would have developed both cerebro-cortical and cerebellar control models for the use of that tool. In other words, you learned through *observation*.

Therefore, people who have never moved in a meaningful, independent way, being confined to a wheelchair, even without the ability to "move" that wheelchair independently at least by having the capability to operate its motor, can still develop the ability to think. And, the knowledge that is acquired can still be derived from sensorimotor interaction. However, all of that "sensorimotor interaction" *is derived from the observation of others*. Observations allow the afflicted individual to learn by watching others. Even interpersonal skills, including learning about the intentions of others, can be acquired through observation [262, 264, 265]. However, in this exceptional example, all of this knowledge is essentially declarative information. And of course, semantic and episodic memory are additionally acquired through the operations of the medial temporal lobe memory system. This must impact upon the quality of cognition, particularly since there is a chronic dependency on others to perform, or at least assist in the performance of, behaviors necessary for adaptation and survival.

This extreme example is in contrast to an individual who experienced typical development and later, in adulthood, lost the ability to "move" because of disease process, including, for example, the symptom of quadriplegia. While this condition can be just as extreme in terms of rendering the person dependent upon others, there is one clue that generates a critical difference; this clue concerns the fact that the individual has personal sensorimotor experience to draw upon. As was indicated, the most efficient procedural and declarative representation of an activity, or behavior, is stored within the neocortex. Depending upon the age of the afflicted person, an individual with a spinal cord injury that results in the extreme example of quadriplegia can continue to rely upon that previous sensorimotor experience to analyze, plan, and organize thinking. Thinking can be creative, innovative, realistic, and adaptive within this population. However, according to Damasio [266], cognition in this population gradually shifts towards a more dependent posture. (It is well known that different disease processes affect different aspects of the CNS; the purpose here is to demonstrate that this proposed model has few, if any, exceptions, instead of hypothesizing how different disease processes affect thinking).

It is also notable the quadraplegia frequently results from spinal cord injuries that occur below the level of the brainstem. This is important because the site of the lesion leaves both reflexive eye movements and frontal control over these movements intact. There is an implicit compatibility between cognitive control and eye movement patterns. Thomas and Lleras [63] demonstrated a significant relationship between eye movement and problem-solving. On a spatial problem-solving task, subjects who moved their eyes implicitly in a pattern that was related to the solution were the best problem-solvers; when they were required to move their eyes in a pattern unrelated to the solution, problem-solving skill deteriorated. In another study, Amador and colleagues demonstrated that patients with Parkinson's disease who were unable to voluntarily inhibit saccadic eye movements performed poorly on three different but simple problem-solving tasks in comparison to normal control subjects [267]. Roberts, Fillmore, and Milich [268] demonstrated that oculomotor inhibitory control was a sensitive indicator of impulse control in adult ADHD subjects, while also revealing a dissociation between oculomotor and manual inhibitory control. Therefore, the dorsal attention network, characterized by reciprocal frontal eye field-parietal lobe connections, appears to play a critical role in the cognitive control, "thinking" system.

The Exceptionality of the Congenitally Blind

If movement and cognition are linked, then it follows that people who are born blind should provide additional clues about the development of thinking. Although more research is needed in the area of cognition and blindness, the few available studies have found various deficits associated with congenital blindness that very likely affect cognitive development. Young blind children are at a much higher risk for experiencing developmental delays and setbacks [269]. In congenitally blind children at school age, there are profound social cognition and communication deficits [270]. Alaerts found that the motor cortex of congenitally blind individuals was significantly less responsive than their sighted cohorts to auditory perception that typically induces motor responses [271]. An investigation by Brambring revealed significant developmental motor delays in congenitally blind children compared to their visually unimpaired peers [272]. Furthermore, it was also demonstrated that visual impairment generates structural and functional changes in the organization of the human brain [273]. In aggregate, even just these few studies imply that the platform for the functional development of cognition is fundamentally disrupted in the congenitally blind. This conclusion follows for at least two reasons. First, it is likely that blind children have more limited opportunities for purposeful movement, restricting the development of "action control" systems. Second, they are deprived of opportunities to learn through observation. There is literally no opportunity for integrating movement with vision, so that the dorsal stream is unable to specify the parameters for the control of action.

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The Exceptionality of Deafness

Deafness represents another area of exceptional presentation potentially important to the development of cognition. Deaf people can observe. However, to refresh the readers memory, in the above discussion of the neuroanatomic organization of large scale brain systems, evidence was reviewed that auditory processes were organized within the functional connectivity profiles of the ventral (VAN) and dorsal (DAN) attention networks. The visual network (VAN), anchored in the occipital lobes, supports the activities of both of these networks. In a review of structural and functional neuroimaging studies, Vaidya summarized the frequent anomalies observed in medial occipital regions in individuals diagnosed with ADHD [274]. There are direct auditory projections to area V1, a medial region of the occipital lobes. As stated above, medial occipital regions are robustly activated on neuropsychological tasks of verbal WM, even though this activity cannot be explained on the basis of "visual processing." V1 is the first brain region to receive "visual" projections from the lateral geniculate nucleus of the thalamus, so within the cortex, this is the well documented region where vision begins [165]. V1 has been traditionally understood as solely related to "visual processing." Multimodal association areas of the parietal lobes, unequivocally involved in the cognitive control functions of the FPN, also receive projections from both visual and auditory information processing systems. It has been proposed that auditory input implicitly evokes images to orient, focus, and guide attention [61, 65, 66]. This raises suspicion about whether or not deafness is associated with anomalies in attention and other aspects of cognition.

A study by Parasinis and colleagues compared the performance patterns of 34 young adults who completed the TOVA, the Test of Variables of Attention [275]. Functional neuroimaging technology was not included in this study. The results found that deaf subjects made more errors of omission, implying higher levels of inattention. However, "impulsivity," as assessed by errors of commission, occurred two to three times more frequently within the deaf participants as compared to hearing subjects. These inhibitory failures were interpreted as deficits in anticipatory control, which very often relates to distractibility. The authors concluded that separate normative standards are required for the deaf and hearing populations,

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since neither group in this study fulfilled behavioral-defined diagnostic criteria for ADHD. However, extreme caution is warranted in this overall conclusion. The TOVA was never intended to serve the purpose of a "litmus test" for diagnosing ADHD; the original intention of the TOVA was to assist in the titration of response to medication in those children who fulfilled DSM criteria for ADHD, and to assist in the assessment of impulsivity and problems of inattention. Similarly, the differences between the categorical DSM diagnostic system and the identification of the neurobiological substrates of symptoms has been differentiated and described in Volume I of this series. Therefore, these findings reported by Parasinis and associates can easily be reinterpreted within the context of the functional properties of large scale brain systems.

These findings are of very considerable significance because they clearly imply a paradigm shift in the way we conceptualize attention. Clearly, attention is not easily dichotomized by the "auditory" and "visual" modalities. It was recently observed that "deaf mice" exhibited disinhibited, impulsive behavior [276]. It was determined that by selectively deleting a specific gene (S1c12a2) from the inner ear, poor impulse control and the disinhibition inherent in hyperactivity were generated. This gene is always found in humans. Furthermore, through a cascade of operations of neurochemical processes, deletion of this gene specifically generates abnormal functioning uniquely within the striatum (the caudate and putamen), a basal ganglia brain region that is an integral component of the numerous frontal-striatal-pallidal-thalamic-cortical "loops" that have been consistently implicated in the pathogenesis of deficits in attention and cognitive control [241, 277–279]. (Please refer to Volume I of this series for additional explanation [2]).

Additionally, an investigation by Hintermair [280] identified significant deficits in cognitive control within a deaf and/or "hearing impaired" population when compared to normal control subjects in item endorsement patterns on the BRIEF [281]. Notably reduced self-control deficits were consistently identified within the hearing-impaired population.

Therefore, when consolidating and integrating the findings from these available studies, considerable support emerges for interpreting behavior, and neuropsychological/cognitive test findings, within the context of identified anatomic reference points of large scale brain systems. Domains such as "visual attention" and "auditory attention" are artificial, misleading concepts. These domains do not reflect how cognition and behavior are organized within the brain. There does not appear to be a fixed assignment of attention organized according to domains of sensory processing. Even though certain commercially available neuropsychological tests purport to measure these "domains" of attention, and although these tests might seem valid on the face of things, it is clear that whatever these tests measure is not so simple. In order to help the field move forward, and to assist in preventing the perpetuation of myths about brain-behavior organization, it is advisable to avoid making reference to this simplified "auditory-visual" dichotomy in neuropsychological test interpretation. In any event, the development of cognitive control appears to be affected in what this selective review identifies as "exceptional cases."

Neuropsychological Testing and Neuropsychological Evaluation: Is There a Difference Between These Approaches?

The ideal way to assess cognitive control is to evaluate the procedural learning that generates automaticity and to assess novel problem solving abilities. Procedural learning is simply not assessed in neuropsychological testing. This does not mean it cannot be done. But there are no commercially available tests of procedural learning. The first step in assessment is to accept this fact. The next step is to apply and integrate what you know into the process of evaluation. Unfortunately, perhaps too many clinical practitioners believe that any diagnostic statement or conclusion must be derived or inferred from a test "score." However, as Albert Einstein also once said, "not everything that can be counted counts, and not everything that counts can be counted." This statement captures the importance of relying upon a variety of sources of data, in addition to test scores, in drawing conclusions. Simply put, if a 12 year old cannot tie shoe laces, why not ask about and observe that child tying shoe laces? There is nothing about that behavior to "score." The observation reveals the motor sequence required for that procedure has not been acquired.

Test scores do not make a diagnosis; tests are tools that clinicians use to guide thinking in making a diagnosis. Clinicians have other "tools" in their toolkit that should also guide diagnostic thinking. There are at least four other "tools" to apply diagnostically. For example, one of these "tools" is the literature, the neuroscientific evidence and knowledge base that directly ties "theory" to "practice." Although the studies and literature reviews cited in this paper represent only a small representative sample, the content of this paper is evidence-based. The knowledge base established in this paper can, and should, develop a framework for thinking about how cognition and behavior are organized within the human brain. The second "tool" concerns obtaining a detailed history about the patient's functioning. Especially within the pediatric population, the prenatal and birth histories are particularly important because this information can provide "clues" that can often predict neurodevelopmental outcomes. For example, if you know the child you are assessing has a history of initial difficulties in "latching on," and/or difficulties with "sucking cycles," and perhaps later difficulties with speech articulation and/or language difficulties, why not actively use that information as part of the integrated diagnostic framework for

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assessing cognitive control? A third tool is observation. If you observe a "hyperactive" child who appears to exhibit vestiges of unsuppressed transitional reflexes, who demonstrates an awkward pencil grip, and who draws and prints by controlling a pencil with whole arm movements, why shouldn't that information be integrated into the diagnostic framework? These observations reveal cognition does not control aspects of the motor system. When you learn that the 14 year old patient you are assessing literally had to be taught to crawl, or perhaps never crawled but walked at an early age, and you observe mild postural and movement anomalies during the assessment, why not use that information in a predictive and diagnostic way? When a parent characterizes their child as a "sloppy, messy eater" because the child often "missed their mouth" when using a spoon, why not interpret that information as a manifestation of a possible failure to develop an appropriate cerebellar control model, and employ the fourth tool of using other tasks that are interpreted as "pathognomonic signs" of disorder, such as administering the neurologist's "finger-to-nose" test or similar tasks dependent upon cerebellar integrity? So, with the current absence of tests of procedural learning, a very strong neuroscientific understanding of functional neuroanatomy, a thorough and well understood developmental history, behavioral observations, and a comprehensive understanding of what tests really measure in contrast to what a test might purport to assess should all be integrated for a comprehensive diagnostic assessment of the cognitive control system. This is what separates "neuropsychological evaluation" from "neuropsychological testing."

Unfortunately, this approach places considerable burden upon the practitioner. There is a vast volume of neuroscientific data relevant to practical neuropsychological evaluation. This information cannot be "spoon fed" to the clinical practitioner; acquiring a foundational knowledge base cannot be acquired by simply attending a few "workshops" to meet the requirements for obtaining continuing education credits. Acquiring the necessary knowledge base requires independent study. Education in this field does not end when the doctorate degree is obtained. In fact, that point only represents the beginning of a neuropsychologist's education because it presumably establishes an appropriate contextual framework to build upon. A graduate education should teach the student how to think about neuropsychology. Even achieving "Board Certification" does not mean the process of independent study is over. There is no single textbook that contains all the information necessary for clinical competence. Neuroscience is simply advancing exponentially. The clinician who is sitting back, waiting for new paradigms and tests of procedural learning to be developed because they believe new tests will solve their diagnostic problems, is only contributing to making neuropsychology an ancillary testing service. Clinical neuropsychology is indeed a tough, demanding profession. Clinical neuropsychology requires the constant independent learning and updating of the practitioner's knowledge base in order to consistently tie theory to practice.

Missing Elements in the Neuropsychological Assessment of EF

There are many reasons why current neuropsychological tests can demonstrate only limited utility in the assessment of cognitive control. One reason concerns the paradigm upon which many neuropsychological tests are developed, which often generates results that focus upon variations of convergent thinking. The second reason concerns the absence of tests of procedural learning. The third reason concerns the lack of adequately assessing the reward system and reward preferences. These features of neuropsychological assessment seem sufficient for opening a discussion about modifying the ways in which we should evaluate cognitive control systems.

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The Traditional Neuropsychological Assessment Paradigm

Most neuropsychological tests are based upon a paradigm that is referred to as serial-order processing. There is a static view of cognition inherent in this model. Three processes are foundational to this paradigm. First, we "perceive;" second, we "think" to formulate a solution to a problem; third, we "act." It is certainly true that this represents one way of generating behavior. However, functioning in this way is a very time and resource consuming process and does not account for how smoothly, quickly, and effectively people are generally able to coordinate and control their behavior. Several relatively recent, seminal papers have reviewed neurobiologic data from various disciplines, concluding there is little evidence to support a "perception-cognition-action" model as the "first and foremost" principle, or the primary, phylogenetically conserved mode of adaptation [104, 282, 283]. This is a "top down" driven model that is insufficient for explaining how people adapt to and behave within their environment. It is true that purposive behavior involves setting goals. These goals set the context for determining the stimulus based behaviors that need to be implemented that achieve the goal. These stimulus based controls are eventually linked to action. This paradigm of problem-solving fits well for both "card sorting" and "tower tests". However, this "perceive-think-respond" paradigm frequently ends with a variation of "convergent thinking." This means that there is usually only "one way" to successfully solve the test problem. This is obvious when considering the WCST [284]; there are only three categorical ways to sort the cards. Tower tests suffer from the same convergent thinking issue; there is only one way to solve the problems within the minimum number of moves. These types of tests are necessary but insufficient for understanding cognitive control. An advantage of these types of tests concerns the fact that from a statistical point of view, these tests can be "normed" very easily.

However, other features of cognition require divergent thinking. Developing effective response options often requires using information and/or objects in a way that is much different from the original intention or use of that information/object. The features of ambiguous problems often require improvisation in defining stimulus-based aspects of issues and using information and objects in a truly

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unique, novel way. This aspect of cognition can best be illustrated with a few additional examples.

When you attend a workshop, you might notice a thermostat on one of the walls in the room. That thermostat is usually encased within a locked plastic box. Without the key to that box, you cannot change the temperature of the room. In order to do so, the socially conforming thing to do is to call the management to open the box to adjust the temperature setting. However, there is another way. Perhaps most of us have witnessed, or tried on our own, to unbend a large paper clip, to insert the tip of the clip into a vent in the plastic box, to then reach the thermostat with that paperclip, and to manipulate it around the temperature dial to change the temperature setting. This is cognitive problem-solving at its best. The stimulus-based characteristics of the problem were identified; the proper tool was not available; however, a simple paper clip was used in a way it was never intended to be used to generate the desired, *anticipated outcome*. Solving this problem required imagination; this imagination was a forward thinking, "off-line" simulation of unbending a paper clip so that it could be used as a "tool" for an extension of a limb, while controlling that action in the manner it was thought about, and by-passing the problematic obstacle of the locked box in the process. Convergent thinking had absolutely nothing to do with the cognitive control that guided the motor system to solve this problem. There could have been multiple, similar thematic solutions. Perhaps a set of long tweezers could have been used; perhaps a specialized screwdriver used to adjust the tension of eye lens frames of eyeglasses could have been used. The critical point is that objects would have been imagined, in an "off line" simulation, to be applied for use in a manner not even remotely related to the original intention of the use of that object. You might call this creativity; you might call this imagination; you might call this improvisation. However, the bottom line concerns the fact that this is cognitive control in operation, with thought, the simulation of object use, ultimately applied to control the motor system to solve the problem.

Similar divergent thinking emerges from revisiting NASA's most "successful failure," the Apollo 13 mission. One deadly problem concerned the increasing build-up of carbon dioxide reaching toxic levels, making it impossible for the astronauts to breathe. The problem could not be solved because the intact, useable carbon dioxide filters that were available in the disabled spacecraft did not "fit" into the compartments occupied by the contaminated containers of the lunar landing craft that was being used as a sort of "lifeboat." Upon reflection, a "one size fits all" design approach would have been more efficient, since these filters serve the same function. However, the disabled aircraft used filters that were shaped like a cube; the filters in the "lifeboat" were shaped like a cylinder. So the problem was one of literally trying to "fit a square into a round hole." Therefore, plastic food storage bags, hoses used for oxygen tanks, the bendable cover of a flight plan notebook, socks, and duct tape were used to construct an "improvised" contraption, a connectional apparatus, to serve the purpose of making a "cube" fit tightly into a "round compartment" [10]. It worked! Similarly, perhaps many readers do not know that Neil Armstrong and Buzz Aldrin, the first people who landed on the moon, were almost "stuck" there [12]! One of the astronauts leaned against a control panel and

Fig. 1 Illustration of divergent thinking to improvise a barbeque pit. Evolution has never relied upon sophisticated cognition as a primary function to solve the problems of adaptation

accidentally broke a switch—the switch that was to ignite the engine of the lunar landing module in order to “lift off” from the moon. Armstrong inserted the point of a pen into the tiny hole left open by the broken switch in order to ignite the engine. Luckily it worked, because ignition of that engine required precise timing. Are these examples of creativity? Certainly! However, it is also high-level cognition, generated by engaging in “off line” simulations of using objects in a way in which they were never intended to be used, after determining the stimulus-based properties of the problem. Therefore, both simple and complex problem-solving situations often share the common feature of divergent thinking—and this requires the “off-line” imagination, emulation or simulation of using objects as they never were used before; this is how the anticipation inherent in cognition guides what we do. Divergent thinking is often necessary when we identify the stimulus-based controls often necessary to solve problems. Figure 1 illustrates a humorous example of how divergent thinking solves the problem of improvising a BBQ pit.

It is not at all clear as to how to evaluate divergent thinking. Evaluations often include the comparison of productivity performances on category word retrieval tasks (convergent thinking) versus retrieving words according to starting letter (a strategy generation task). Koziol and Budding [1] have described different patterns of performance on these tasks, one of which possibly corresponds with the strategy generation that likely plays a role in supporting divergent thinking (pp. 232–233). However, it remains unclear as to how this corresponds with cognitive deficits in the “real time” observation of problems in the performance of an individual’s daily activities. Once again, we engage in behaviors that are routine a very substantial part of the time. It is likely that a failure to automate these behaviors already reflects a failure within the cognitive control system.

Nevertheless, word generation tasks do provide a clue about developing tasks of divergent thinking. Examples of such tests might include instructions such as, "tell me all the ways you can think of for using a paper clip;" "tell me all the ways you can think of for using a clothes hanger;" "tell me all the ways you can think of for using a pen or pencil;" "tell my all the ways you can think of for using a chair." The list of content possibilities is open to the reader's imagination. However, these variations of "idea generation" tasks would start to tap into an individual's capacity for divergent thinking, and to that extent, this would provide a rough index of one aspect of problem-solving, albeit indirectly. In any event, productive performances on tasks of this type would certainly require the "off line" simulation about ideas for object usage. If these types of tasks were standardized, it is likely that a range of performances would be obtained that do not follow the normal distribution of a bell-shaped curve.

In fact, if brain-behavior relationships are well understood, the divergent thought processes of the neuropsychologist can be used to "improvise" a neuropsychological evaluation. Dr. E. Goldberg once stated that if necessary, he would choose to use a "can opener" as his main evaluation administration "tool" (Personal communication, 1996). The author of this paper is perhaps less imaginative, preferring to use an ordinary deck of playing cards. In fact, the author has used this idea as a question in the final examination for a graduate level course on neuropsychological evaluation. Students were presented with one global essay question: *Using your knowledge base of functional neuroanatomy, devise all the tests you can, relying upon everything you know, and only a deck of ordinary playing cards, to administer and interpret a neuropsychological evaluation. Your answers must include the informal assessment of as many relevant brain functions as possible. You have one hour to complete this exam. There is no provision of extra time*.

Although we all concede that traditional problem-solving tests are useful, we also must be mindful that much of human, and animal behavior, is automatic and outside of conscious cognitive awareness. Just as a monkey in its natural habitat is not performing a "delayed non-matching to sample" working memory task, a human is not sorting cards or solving tower tests in his/her natural environment. Instead, as we have indicated, the vertebrate brain is in almost constant interaction with the environment; sensorimotor processing is continuous. Organisms benefit from the experience of interacting with the environment. To reiterate, it has been estimated that a very substantial percentage of behavior is automatic [114, 115, 169]. We very often do things that simply need to be done. Adaptive functioning is characterized by alternating episodes of automatic behavior, switching back and forth to other episodes of behavior that require redirection and/or problem-solving through higher-order controls. Therefore, neuropsychology needs to incorporate tests and procedures that measure the individual's ability to benefit from environmental interaction; tests that evaluate learning through activity are necessary; in other words, tests of procedural learning and memory are needed, exactly what is currently missing from neuropsychology's test arsenal. Neuropsychology needs to add the paradigm of benefiting from the experience of interacting with the test; neuropsychological assessment needs to measure the individual's ability to benefit from "doing."

In other words, neuropsychological assessments need to include the identification and measurement of certain types of "practice effect."

In no way, shape, or form is this a "rogue" idea or proposal. Neuropsychology already uses the idea of a type of "practice effect" paradigm without necessarily thinking about or reflecting upon it or calling it that. For example, what occurs on a word list learning task? An individual is read a long list of words, and the person's performance is recorded over multiple trials; a positive, incremental "learning slope" is expected, because this reflects learning, or acquisition of the word list. This learning through repetition is *practice effect.* However, this type of learning is the function of the medial temporal lobe memory system. It reflects the learning or acquisition of semantic, declarative knowledge. The newly learned information is stored or retained in posterior cortices, in sensory-perceptual cortices that lie posterior to the central sulcus. If a practitioner has an understanding of the functional neuroanatomy of the MTL, he or she can likely use a variety of different tests to evaluate the integrity of this system [285].

However, neuropsychology needs to expand its evaluation "tool kit" by assessing the acquisition of behaviors that are retained in anterior cortices, including the premotor cortex. These anterior brain regions play a very significant role in a person's ability to benefit from interacting with the environment. This includes the acquisition of *procedures.* We need to at least begin to understand how a person learns *activities.* This can be accomplished in a simple way that follows the sensorimotor interactive paradigm of cognitive control described in this paper.

For example, the original Trailmaking Tests are within the public domain. These tests can be administered as procedural learning tests. For example, if a subject is unable to complete Trailmaking Test Part A within the timeframe of the normative standard, and in an error-free way, that test should be readministered. After multiple presentations of the exact same test, speed of performance should improve and errors should be eliminated. This represents the learning of the "procedure" of performing the test, while according to neuroscientific theory, the quickest, error-free performance would demonstrate the most efficient representation of the behavior stored within anterior cortices (it is fully realized that the sensory-perceptual processes required to complete the test recruit posterior cortices, consisting of an integrated task "network." The example presented in this way is for purposes of simplification to demonstrate the need to evaluate the learning and automation of "activity" brain systems).

Trailmaking Test Part B is the more difficult task because it recruits the cognitive function of the FPN, keeping much more changing information in mind for successful completion of the task. However, the principle is the same. With repeated trials of the test, accuracy should increase and speed of performance should decrease as the cognitive and motor aspects of the task are learned and automated through "practice effect." This improvement in performance would reflect a dynamically changing neuroanatomy switching from the initial control of the FPN to the motor "loop." In other words, this would be associated with a decrease in reliance on initial cognitive control towards the type of task acquisition that leads to automaticity. The exact same argument can be made for using the repeated administration of maze tasks for the purpose of evaluating aspects of procedural learning. The subject would be learning the procedure of solving the maze by directly interacting with it, in other words, learning by doing or "action control." Improved performance, by decreasing time to completion and errors, would again reflect increased automation and decreased reliance upon the guidance of the FPN.

The beauty of this methodology is that it does not necessarily require extensive "norming." If a subject has adequate motor control, and if a subject knows the numeric and alphabetic sequences (which are fundamental task requirements to begin with), any given subject acts as his or her own "control." Learning, or benefiting from participating in the task, is assessed by observing improvement over multiple trials. The subject is not compared to an "external" group standard. The individual is compared to himself/herself over multiple trials. This methodology was first introduced many years ago by Reitan [286], and it is referred to by Lezak [16] as an individual comparison standard. There is no need to convert a raw score to a standard score and to statistically develop a "normal distribution" or "bell-shaped curve." There is no need to develop a percentile ranking to characterize performance. Terminology emerging from this type of scaling such as "average," "low average," or "borderline," etc., is completely irrelevant and misleading. The only variable of interest concerns learning as demonstrated through improvement in performance [102, 165]. Space considerations do not allow for an exhaustive review of how this test and methodology can be applied to additional tests and formats for administration. The relevant points concern the fact that the identification and measurement of this type of learning is necessary, quite possible, while falling back upon an interpretative methodology that has been well recognized for over the past 50 years, yet seldom implemented in today's neuropsychology.

And from a practical point of view, what would test results like this tell us? Data of this type would provide clues about understanding the person's ability to automate; improved performance would represent the acquisition of new motor sequences which are essentially routines. Therefore, information of this type might provide meaningful clues as to why children learn certain aspects of academic tasks, and even personal routines, including hygienic motor procedures, very slowly, if at all. The inability to improve performance on tasks such as the Trailmaking Tests and even other tasks such as the older Wechsler Mazes would essentially be saying that every time the task is performed, it requires the guidance of the FPN in constant interaction with the DAN. We would be measuring "processing speed," which is essentially a by-product of cognitive control. In other words, lack of improvement would be telling us that on each and every administration of the task, it was as if that individual would be performing the task for the first time. This is meaningful information that can readily be applied to intervention and treatment plans, which unfortunately, are topics beyond the scope of this paper. In any event, if cognitive control systems must co-exist with the automation of procedures, evaluations need to include an assessment of how an individual benefits from the repeated experience of interacting with procedural tasks that eventually lead to the *implicit control over behavior*. Perhaps research versions of these procedures can be developed for the purposes of correlating these types of test results with the performance of practical, routine behaviors.

The posterior lobes of the cerebellum are also active during the course of procedural learning, especially with respect to the acquisition of motor sequences [287, 288]. It remains unclear as to exactly how the cerebellum contributes to this learning, although its critical role in anticipatory control has been described above. The fact of the matter is that basal ganglia and cerebellar systems interact, as was referenced earlier. It has been proposed that improvement in performance should be interpreted as motor adaptation governed through the cerebro-cerebellar circuitry system and that the long term retention of motor sequences, or automation, is dependent upon the recruitment of the corticostriatal system, where new motor sequences are originally programmed and later retained [157, 288]. This learning process was illustrated in Fig. 1 of chapter “Cognitive Control, Reward, and the Basal Ganglia”. In that case, improvement in performance on tasks such as the Trailmaking Tests and Wechsler Mazes would be recruiting the functions of both systems. This viewpoint also makes intuitive sense, since both systems which organize the brain vertically operate in tandem instead of in isolation. Njiokiktjien [183] has proposed that cerebellar pathology is the cause of the slowed learning of actions that depend upon adaptation to environmental change. There appears to be less information transfer of automatization of a behavior to the same behavior or action with other circumstances. In any case, it is critical to assess these systems not for the purpose of brain localization properties because the viewpoint presented in this paper emphasizes functional integration. The purpose for identifying and characterizing the functionality of these systems concerns the fact that these vertically organized brain networks represent the foundational platform for the development of the cognitive control system.

Nevertheless, the Prism Adaptation task has been demonstrated to be dependent upon cerebellar integrity. The subject learns to hit a target with a form of a dart; after task acquisition, the subject is given prism glasses which displace the target 10–15 % in a different direction; the subject is required to relearn the task under the conditions of this displacement. After this new task acquisition, the subject is required to re-adapt to the task under the original condition. This task has been demonstrated as extremely sensitive to the integrity of the cerebellum, and without question, this task can be easily adapted to the clinical situation by using currently available electronic technologies [289].

The Motor Examination

Because of the nature of development, with its dependence on sensorimotor interaction, an assessment of motor functioning is critical to a meaningful evaluation of the cognitive control system. In this regard, a motor examination should be considered critical to neuropsychological evaluation, particularly within the developing pediatric population since cognition is grounded sensorimotor behavior. Results of motor examinations, as reported above, are predictive of later cognitive control. Motor examinations should be systematic, and unfortunately, most commercially available neuropsychological assessment tools do not include systematic motor assessment. Many commercially available exams are multiple-component subtests that are organized idiosyncratically, instead of respecting the way in which motor behavior is organized within the human brain. Certain existing motor exams typically focus on aspects of unimanual and bimanual motor programming tasks which are clearly extremely useful. Abilities to perform these types of tasks emerge at around the age of 5 years, while the motor system stabilizes, with adult levels of performance expected sometime between the ages of 10 and 12 years [183, 290]. These tasks are difficult to norm, as inter-rater reliability can be difficult to achieve (Goldberg and Podell, independent personal communications, circa 2007). However, as a general rule, the three brain regions participate in motor activity in different ways, and this has potential localizing significance. Programming motor sequences is the property of frontal lobes [64, 165]. Intention programs, such as starting, perseverating, and stopping behaviors, as well as the lack of inhibition over voluntary movement, is basal ganglia governed [111, 195, 291]. Managing the coordination, or the rate, rhythm, and force of movements, in other words, the *quality* of movement, is under cerebellar control. In this regard, qualitative observations can be extremely important in interpreting the data obtained from motor examinations. A neurologist routinely relies upon this type of information. Why can't a neuropsychologist do the same?

This paper did not cover the functions of the cerebellum as a whole in a detailed way, since the focus of the paper was primarily upon cognition, much of which is modularly organized within the neocerebellum, and because space limitations generated a practical publication issue. However, the spinocerebellum, the

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vestibulocerebellum, and the neocerebellum are all relevant to human development and play significant roles in postural control, balance, proprioception, coordination, and therefore, in general, controlling the quality of movement. Many of the functions of these regions are "on line" early during infancy and the toddler years, and are currently often assessed by occupational therapists. However, since these functions are part of the platform for motor and cognitive development, neuropsychology needs to incorporate aspects of occupational therapy training into its pediatric educational curriculum. In the meantime, it is important for the pediatric neuropsychologist to examine occupational and physical therapy records and to keep in mind that even though a developmental "delay" may have been treated and resolved, that fact that the delay occurred might be the much more critical variable that planted a seed for the emergence of a subsequent neurodevelopmental disorder that impacts upon the development of the cognitive control system.

In addition, there is absolutely no reason whatsoever that a neurologist's finger-to-nose test, or a heel-to-toe walking test, or a balancing on one foot test cannot be easily incorporated into neuropsychological assessment across age ranges. For example, law enforcement officers are trained to use these screening tests to assist in determining whether or not a person might be driving under the influence of alcohol, since alcohol has an affinity for affecting cerebellar control models. Surely a neuropsychologist can be trained to use these, and other screening procedures, to assess the integrity of certain cerebellar functions. Perhaps it was irrelevant when all meaningful behavior was considered under cortico-centric control. However, at this time, there is absolutely no arguable defense against using these screening techniques to assess cerebellar integrity. However, in order to administer and interpret these types of test results, a paradigm shift is required in neuropsychology that incorporates the importance of understanding control over the motor system in the development of cognition. The PANESS [292] is a relatively brief examination that is readily available, while it assesses the presence or absence of many "soft signs" which are often a manifestation of the integrity of motor system development which is associated with cognitive control. Recent neuroimaging data demonstrate that neurological soft signs (NSS) are not so "soft" because they have been associated with both structural and functional regional brain anomalies [293]. Njiokiktjien [183] has described an approach for assessing the development of motor abilities in children that taps a variety of motor systems in a systematic way. Although not commercially available in the USA, the examination is available for purchase through the European market, while the procedures administered are described in the above cited reference.

The Evaluation of Reward Preferences

Another reason that neuropsychological tests have limited applicability in the evaluation of EF concerns the emphasis on "thinking" mechanisms, without considering the implicit reward system. As things stand right now, just about all neuropsychological tests go through dorsal-lateral information processing channels [294]. Tests that evaluate orbital and medial cortical regions and ventral subcortical "reward center" regions are not in the neuropsychologist's tool kit. The functioning of these brain regions are well known as difficult to measure [295].

This paper presented EF within a problem-solving paradigm. In doing so, a cognitive control system emerged that was in part based upon the anticipation of reward outcomes. It was concluded by reviewing phylogenetic and longitudinally-based neuroimaging evidence that the development of cognitive control is a "bottom up" process, and that as higher-order control over behavior develops, lower-level behavioral controls are not replaced. Instead, lower-level and higher-level behavioral control mechanisms *co-exist.* Choices and decisions about behavior are based upon the anticipated outcomes of those behaviors. These expectations or predictions are rooted in reward assignment/associations and the individual's reward preferences. These rewards are hierarchically organized and can be tangible or "fictive." Much of this is based upon instrumental learning that lies outside of the domain of conscious, voluntary control. In order to assess these functions dependent upon medial, orbital, and ventral brain regions, tests need to be administered that lie beyond the control systems of the prefrontal dorsolateral and FPN networks; tests that either by-pass or minimize reliance upon the dorsal-lateral channel need to be included in the clinical neuropsychologist's assessment tool-box.

Neuropsychological evaluation seldom even remotely considers reward preferences as a relevant variable. For example, we all know of people who work extremely hard to avoid negative outcomes; others seem insensitive to negative reward value, and frequently engage in behaviors that have the potential to bring only positive outcomes or rewards. Although it might seem odd to mention in a neuropsychological paper, the "account executives" of the investment industry appear to be more "tuned-in" to assessing people's reward preferences than clinical

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neuropsychologists! Account executives routinely evaluate a client's risk tolerance profile before purchasing investments. This tolerance profile is actually a form of reward preference evaluation because it assesses the person's level of ability to tolerate risk, uncertainty, and the potential lack of reward, and loss, inherent in risk and ambiguity. At base, this is a type of assessment of the ability to take risks in the hopes of receiving reward, or the preference for avoiding loss, or negative outcome, at all costs. Perhaps neuropsychology can take a very simple, initial step forward by devising questionnaires that assess similar preferences. This approach might at least provide certain types of information about the reward based decision-making process of the cognitive control system.

The Iowa Gambling Task was originally designed to assess the reward circuitry system, but its effectiveness has received mixed reviews [296, 297]. An experimental version of this task exists for children, but this procedure is not commercially available for clinical application. "Discounting" paradigms have been used to study reward sensitivity in children, but this paradigm clearly has a strong component of cognitive mediation, and the paradigm once again is not available for clinical application. It is also critical to recall that from childhood through adolescence and adulthood, the reward system can reorient, so that reward preferences are certainly not a static entity [298].

The experimental literature has demonstrated significant utility in assessing reward preferences by employing the "probabilistic category learning" task [6, 184, 245, 251, 299–301]. In this paradigm, a subject is required to classify abstract stimuli into categories, and while they are informed about reward outcome by being told they are "right" or "wrong" after each trial, this positive and negative outcome information is accurate only a certain percentage of the time, or on a certain percentage of trials. Because of the highly abstract nature of the task, conscious cognitive mediation has no bearing on task performance; it is essentially by-passed. When subjects perform this task, they feel as if they are guessing on each and every trial. This task has proven to be extremely sensitive to an individual's reward preferences, not only in normal control subjects, but also in a variety of different patient populations. The essence of the task evaluates whether an individual learns more quickly in response to positive outcomes or negative outcomes. Again, statistical norms such as standard scores or percentile rankings have little or no bearing on test interpretation. These types of statistical manipulations are totally unnecessary for attempting to "standardize" or "norm" the test. The only variable of interest concerns reward preference. A task of this type has considerable promise for objectively evaluating the reward characteristics mediated by the ventral striatum. The weather prediction task, developed by Knowlton, Squire, and Gluck [302], is another primary example of probabilistic learning. Although this task has not been utilized in recent research investigations, it remains potentially useful. It was never made available for commercial use, although there is no reason why it's possible clinical use cannot be investigated.

Motivation grows from reward preference, and this type of reward information is considerably more important than might initially meet the eye. Clearly, motivation and reward are critical to decision making. However, in recent years the field of clinical neuropsychology, especially when operating within forensic settings, has become preoccupied with "effort testing." Inferences made from "effort testing" frequently place the patient in an unfavorable light by implying the individual exerted only suboptimal effort during the neuropsychological evaluation. But what if a dysfunctional reward circuitry system is a fundamental aspect of the individual's presentation? In those circumstances, the results of "effort testing" would be misleading and would be a disservice to the individual who was evaluated. "Effort testing," which is purely based upon a statistical methodology having nothing at all to do with an individual's reward preferences or inability to maintain motivation, has never considered this possibility in testing development. This potential misuse of "effort testing" findings only underscores the need for a direct evaluation of the reward system. Neuropsychology is the study of brain-behavior relationships; it is not at all clear how a statistical methodology based upon a "less than chance" level of performance relates to the brain-behavior relationships of reward and motivational circuitries.

From a neuroanatomic point of view, "effort" and "symptom validity" testing make little sense given the current state of knowledge about brain function. For example, considerable activity is occurring within the brain when we are relaxing, sitting around doing nothing. Neuroimaging studies have consistently identified a Default Mode Network (DMN) which is considered to reflect the physiological baseline of the brain. Anchored in the anterior medial prefrontal cortex and the posterior cingulate cortex, these regions recruit activity within the dorsomedial prefrontal and medial temporal lobe memory systems when we are at rest. The DMN likely includes our experiential history, when we are sitting back, perhaps thinking about what we have previously done or what we would like to be doing, inferred from this pattern of regional brain activation. Activation of this network is also noted when a person experiences lapses in attention. However, when we are participating in a cognitive task, the DMN is less active. By definition, participation in "effort" testing is a cognitive task, which should decrease DMN activity. The Word Memory Test (WMT), developed by Green [303], is often used as a measure of effort and symptom validity. The task was designed to be extremely easy, without requiring effort, presumably placing minimal cognitive demand on the examinee. Allen and colleagues [304] used fMRI to investigate regional brain activity in a small sample of four young adult normal control subjects who had absolutely no incentive whatsoever to perform poorly on the WMT. The results did not demonstrate activation of the DMN. Instead, the right hemisphere DLPFC, the left middle frontal gyrus, the dorsal anterior cingulate, the bilateral anterior insula, the bilateral superior and medial regions of the parietal lobes, and the ventral occipital gyrus were robustly and consistently activated. These same brain regions are identified as areas involved in the FPN, the visual, ventral and dorsal attention networks, and the "salience" network, which are all activated when tasks require attention, cognitive control, and effort. The authors concluded these findings represented compelling evidence that the WMT is clearly not an "effortless" cognitive task. However, by implication, any clinical presentation with impairment in any of these brain regions would theoretically "fail" the effort testing task for reasons other than malingering or a conscious lack of effort. In a subsequent study, fMRI and WMT performance data were available both one year before and one year after the same individual sustained a traumatic brain injury. Although WMT results were quite similar, the fMRI data revealed a pattern of much more widespread brain activation post-injury, with considerably more recruitment of the FPN hub, implying that even greater cognitive effort was required to maintain the same initial accurate level of WMT performance [305]. These studies generate significant questions about what “effort testing” really means. Considerably more research is required before the results of these tests can be interpreted with clinical confidence.

Summary, Conclusions, and Future Direction

In keeping with Einstein's quote used to introduce this volume, an attempt was made to understand EF by trying to simplify and identify its stimulus-based characteristics. EF represents an ambiguous issue. Ambiguous problems cannot be solved unless the stimulus-based properties of that problem are identified and understood. However, after making a comprehensive search to identify these properties of EF, only two stimulus-based control systems were identified. These two systems are the cerebro-cerebellar and the cortical-basal ganglia vertically organized brain systems. The cerebro-cerebellar system operates on the basis of predictive or anticipatory control. The cortical-basal ganglia system functions within the principles of reward-based instrumental learning. These two motor control systems always operate together, in tandem, as parallel processes. It was concluded that during the course of phylogenetic development, these two systems expanded generating a cognitive control system that was required to meet the increasingly complex demands of interactive behavior. The cognitive control system essentially merged anticipatory control with hierarchically organized "rewards" to meet the needs of adaptive behavioral control. This system did not emerge for the purpose of thinking. Instead, cognition evolved from these systems to serve the needs of interactive behavior. An "executive" could not be identified. Instead, the neuroscientific evidence identified a behavioral control system that was characterized as a task-dependent, dynamically changing locus of control, requiring the activation of multiple large scale brain networks. Therefore, this simple problem-solving approach actually banishes the artificial EF concept in favor of a neuropsychologically inspired cognitive control system which relies upon all the stimulus-based properties necessary for motor or "action control."

It was also observed that evolution's oldest and conserved solutions for generating adaptive behaviors have never involved sophisticated cognition or conscious cognitive control. Nature's solutions to the problems of adaptation have always been biologically economical, conserving the energy required for sophisticated cognitive processing. By divesting language from its presumably central role in hemispheric specialization, the biologically economical novelty-routinization principle was

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uncovered and applied to explain over 500 million years of evolution of the vertebrate brain. This principle requires the co-existence of automatic behaviors along with cognitive control mechanisms. Automatic behaviors, either innate or running on the basis of acquired associations, allow for exploiting or taking advantage of the predictable and routine features of adaptation. Cognitive control allows for the learning of new behaviors in order to adapt to novelty or the unpredictable aspects of the environment. The co-existence of these two systems functioning within this principle allows for optimal behavioral adaptation, while simultaneously explaining the dynamically changing locus of control of behavior. In fact, successful adaptation is impossible to achieve without this "dual tiered" and hierarchically organized level of behavioral organization.

Neuropsychology appears to do a reasonably good job of assessing the processes of sensory-perceptual persistence, or semantic and episodic memory, just so long as test interpretation is based upon the neuroanatomic organization of the medial temporal lobe learning and memory system. However, critical components are missing from the neuropsychological evaluation of the overall cognitive control system. These features concern the assessment of how an individual benefits from interactive experience, in other words, procedural learning and adaptation; the ability to benefit from activity, retained within anterior cortices. Another feature concerns the evaluation of the reward system. The cognitive control system is a product of both of these vertically organized network systems. Therefore, the functions and processes of these systems need to be evaluated in order to effectively assess cognitive control. Clinical neuropsychology has not recognized that the brain evolved to control activity, and not for the primary purpose of thinking. The traditional paradigm of "perceive, think, and respond" is useful in understanding task dependent problem-solving. However, an interactive paradigm that includes the learning of activities and procedures, as well as reward preferences, also need to be included in evaluation because cognitive control processes are derived from these two basic behavioral adaptation systems. Additional future directions for neuropsychology concern keeping abreast of neuroscientific findings. Since certain neuropsychological tests are successfully used as probes in the investigation of brain-behavior relationships, care should be taken to incorporate the exact same testing paradigms into the neuropsychological evaluation process. As was duly noted, even slight changes in test characteristics recruit different brain networks than those involved in the original studies. Employing the same tests used in clinical and research investigations would increase the likelihood of evaluating the same brain systems. This is in striking contrast to the current practice of using tests that have been developed and even subsequently revised or updated from an a-theoretical perspective, which can never link theory to practice.

So, "that is the story. Do you think there is any way of making them believe it? Not in the first generation, but you might succeed with the second or later generations." Perhaps this quote from Plato places neuropsychology in the exact same position from which this review originally began. What we see primarily depends on what we look for. Maybe we are right back where we started.

Addendum

"Change is the law of life. And those who look only to the past or present are certain to miss the future."—John F. Kennedy

"In times of rapid change, experience could be your worst enemy." —J. Paul Getty

Introduction

Knudson [306] proposed a comprehensive model of attention that recognized the role of certain subcortical structures and implicit processes in decision-making behavior. Within that model, the guidance of working memory and the modulation of the strength of neural signals necessary to make choices and decisions remained a process under neocortical control. Despite input from underlying brain systems which operate implicitly, the proposal was based upon top-down volitional control. This is just one illustration of the persistent, perseverative focus on the role of the neocortex in human cognition. A significant body of neuroscientific evidence has emerged to challenge this type of cortico-centric viewpoint. Koziol and Budding [307] were arguably the first to integrate a substantive literature which emphasized the critical importance of subcortical structures in cognition, examining both explicit and implicit processes. That manuscript, which was primarily written for the practicing clinical neuropsychologist, focused upon the vertical organization of the brain. Implications for neuropsychological assessment were reviewed. Neuropsychological evaluation procedures and interpretative strategies were proposed. Volumes I and II of this current series on "*the vertically organized brain*" are essentially an update of the original 2009 manuscript. Since the submission and acceptance of Volume II in the late summer and mid-fall of 2013, considerable influential neuroscientific literature has emerged. Although this addendum was written to cover these relevant data points, the author readily admits that new findings are developing so rapidly that any review can no longer be considered "comprehensive." Instead, all conclusions represent "interim" solutions. This addendum

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focuses only upon the literature published within the past few months to support, expand upon and further summarize the "conclusions" offered in the first two volumes of this series. However, since this new literature opened-up other related areas of investigation, a small handful of references available previously were included to illustrate and integrate certain critical points. This postscript is organized from the perspective of "bottom-up" phylogenetic development which captures the essence of the initial approach taken in 2009, and which is evident in Volume II.

The Phylogenetic Evidence

In the early evolution of the vertebrate brain, cerebellar, basal ganglia, and brainstem regions predominated over the relatively small volume of the cortex. As the phylogenetic scale is ascended, the cortical mantle expands, but primary and secondary sensory systems are most apparent within the cortex. These systems are linked to sensory-motor hierarchies. However, in the primate, and human, the cortex becomes populated by cortical association areas. It is widely known that evolutionary development is not simply characterized by greater numbers of neurons. Instead, the cortical mantle is populated by distributed brain networks. Certain networks are observed in other primates. However, neuroimaging studies demonstrate that in humans, the neocortex features at least seven consistently identified large scale distributed brain networks [308]. These large scale brain systems preserve connectional "looped" architectures with the cerebellum and the basal ganglia in an extremely orderly manner, as is evident in the brains of other vertebrates as well [309]. As previously reviewed, in humans, these networks include connections that are not observed in other species. This represents the expansion of the cerebro-cerebellar and the cortical-striatal systems. This illustrates the developmental expansion of these two systems which define the vertically organized brain and the architecture of the cognitive control system. However, just as importantly, this reveals neurobiologic consistency; the "gap" once believed evident between the capacities of the human brain and certain cognitive abilities observed in other species is no longer a "mystery." A keen awareness of this consistency, which continues to be demonstrated in the most recent studies, is absolutely critical for a comprehensive understanding of this ebook series.

The Neurodevelopmental Evidence

The human brain goes through a protracted series of multiple changes known as neurodevelopment. This process includes the formation and organization of functional networks that eventually support complex cognitive systems. Cognition is dependent upon dynamic, changing interactions between widely distributed brain regions as they mature with age. Menon [310] combined the findings of a range of investigative techniques to outline the course of this maturational process. It was also demonstrated how this knowledge informs us of the origins of many childhood onset, adolescent, and even certain adult-onset psychopathologies.

Six conclusions were derived from this seminal paper. First, the neuroanatomical “backbone” from which functional brain networks emerge is mature by 2 years of age. This finding seems to emphasize the critical importance for these systems to become functionally “on-line” at an early age for normal development to occur. It is no simple coincidence that this is the age during which the toddler learns through interacting with and exploring his or her environment. This observation continues to reflect the conclusion that knowledge is derived from sensorimotor interaction, and that these systems, though not yet fully developed, must be in place and operative for typical cognitive control to eventually emerge.

Second, functional brain circuits are segregated. However, the developmental process initially features stronger short-range connections in children and shifts to stronger and more distinctive patterns of long-range connections between distal brain regions in adults. Third, a major feature of functional brain network development involves the reconfiguration/reorganization of cortical-subcortical connections. Cortical-basal ganglia circuits which are critically important for reward, motivation, habit formation, and incentive-based learning go through a significant cascade of changes in connectivity patterns between childhood and adulthood. Again, this is one of the brain’s vertically organized systems that plays a central role in motor, affective, and somatosensory functioning, in other words, cognitive control [311]. Volume I presented a model of brain-behavior relationships using ADHD as proxy. However, this system of cortical-subcortical connections is disrupted in several major neurodevelopmental disorders [312–315]. Awareness of this developmental pattern opens the door for understanding all sorts of practical behaviors. Similarly, while Volumes I and II highlighted the subthalamic nucleus (STN) as a basal ganglia region of primary importance in “stopping” behaviors, current evidence recognizes the STN as a key structure responsible for modulating cortical and subcortical activation patterns that are essential for generating emotions and feelings [316].

For the purpose of practical application of these findings, childhood tasks such as washing and bathing, dressing, and doing personal chores that should become routine are essentially derived from “habit formation.” The lack of acquisition of these behaviors can now be understood as a failure to establish habits, essentially a breakdown in procedural learning systems, governed by the basal ganglia. These habit formation failures reflect a lack of automation, and therefore, they are predictive of later poor cognitive control. Failures in reward and incentive-based learning can generate motivational difficulties, influencing the ability to associate meaning to context. In order to develop the ability to plan, every child must learn when and in what contexts to expect events to occur. Firmly establishing these associations are a requirement for generating efficient automatic behaviors. When these “associations” are not stable, it becomes difficult to detect, and/or “predict/anticipate,” regularities and changes in the environment. This would generate problems in modulating behaviors, “shifting” between different activities, and generally interacting with surroundings that are dynamically changing. In children, adolescents, and adults, primary interactions with the world are characterized by automatic behaviors that alternate with episodes of cognitive guidance. This depends on interactions within fronto-striatal-thalamic circuits [317]. Attention "switching" and "cognitive flexibility" are contingent upon the integrity of white matter microstructure of the basal ganglia [318]. These findings highlight the crucial role of the basal ganglia and fronto-striatal-thalamic circuitry profiles for cognitive flexibility, which is a critical component of cognitive control. As a general conclusion, the degree of striatal activation is a determining feature for the conscious and unconscious decision-making of attentional selections, the strength of cognitive guidance functions necessary for "multitasking," and, therefore, cognitive flexibility [319].

A recent review paper has integrated the critical features of goal-directed behavior [320]. This behavior clearly requires correct selections of attention and action, planning, and execution. The ability to flexibly adapt behavior when performance problems and or environmental changes occur was again highlighted as a critical factor. The continuous monitoring of the course and outcomes of one's behavior, knowing how well or how wrong things are going, is the prerequisite for determining the need for, the type of, and the magnitude of flexible adjustments, which defines cognitive flexibility and control. Feedback control loops, inherent as a design characteristic of the brain, are a primary feature of adaptation at all levels of the central nervous system. This not only demonstrates the neurobiologic consistency of the evolution of the vertebrate brain, but also, nature's tendency to reuse the efficient features of existing modulatory control mechanisms instead of generating totally "new" mechanisms. With respect to cognitive control, cortico-striatal and cerebro-cerebellar "loops" are the underpinning of modulatory processes. Ullsperger and colleagues [320] reviewed both animal and human studies, and from that data, they outlined the physiological principles of performance monitoring, the succeeding autonomic, motivational, cognitive, and behavioral adaptation, and directly linked them to the supporting neuroanatomical and neurochemical substrates. They also integrated these neurobiologic underpinnings with psychological theories and computational models. The data reviewed are consistent with Menon's developmental principles.

Menon's fourth developmental principle relates to the well known process of "prunning." This process is usually conceived as rewiring connections at the synaptic level. However, this process is also evident at the systems level. This essentially reconfigures and rebalances functional connectivity in the developing brain. Therefore, any given task might theoretically recruit different "profiles" of functional connectivity at different ages. This finding leads to the fifth principle. Functional connections within and between the seven independent large scale brain systems undergo significant changes during the course of development. For example, the salience network and the insula demonstrate weak functional connectivity in the early phases of brain development. Because of the significance of this system for adult cognitive control, this network can be a source of vulnerability for abnormal development during the processes of the typical reconfiguration and rebalancing that should occur, therefore generating neurodevelopmental psychopathologies. Volume I of this series reviewed a variety of behavioral aberrations that occur as a manifestation of hyper and/or hypoactivation within these systems, which were also reviewed within the text of Volume II. Finally, brain development features a dynamically changing landscape of excitatory-inhibitory balance. Aberrations in this “balance” can impact upon patterns of large scale brain system connectivity. Minor alterations in this balance between excitation-inhibition can easily account for individual differences in cognitive ability patterns, but significant imbalances would generate aberrant brain connectivity resulting in many of the cognitive, affective, motivational, and motor symptoms observed in a variety of neurodevelopmental disorders, from the varied symptoms seen in ADHD all the way through to include Schizophrenia, also accounting for certain symptomatic overlap.

These updated findings were reviewed to keep this volume current, to integrate this information, and also because of practical considerations. Pediatric neuropsychological evaluation is essentially an assessment of a “moving target.” The traditional view is that neurodevelopmental disorders require multiple evaluations over time, primarily for assessing progress after comparison with an initially established baseline. However, evaluating a child really does represent a snapshot, sort of a photograph that “looks different” as a child grows. Repeated assessments, at appropriate intervals, should be understood within the context of changing patterns of brain system connectivity. Performance of a task at “baseline” assessment might recruit a particular set of brain systems, while subsequent assessments conceivably recruit different brain networks in the performance of the same task at different ages. There is no simple correspondence between task performance and brain system development that is currently identified as a universally accepted standard at any age. It is impossible to identify or label any brain region as contributing or not contributing to any motivated behavior [321]. Instead, it is necessary to consider the specific circumstances under which the brain region, or system, is being recruited, and these “circumstances” include developmental age and aberrant brain development. These “principles” of development proposed by Menon assist in interpreting changes in test performances frequently observed in typically developing children as well as in pediatric pathologies. These principles assist in explaining dynamically changing behavioral presentations over time. This also provides an understanding of what has traditionally been termed the “outgrowing” of pathological symptoms as distal brain regions strengthen during the course of development. However, these principles also generate an underpinning for understanding why certain developmental pathologies emerge only slowly, why “new” symptoms can emerge over time, and why some symptoms might even appear to worsen. This only underscores the necessity of closely monitoring and re-evaluating the functional status of neurodevelopmental disorders over time, at appropriate intervals. In fact, these principles speak very strongly towards the necessity of developing new neuropsychological evaluation paradigms for assessing certain features of an individual’s functioning that are not even remotely considered in current neuropsychological assessment approaches, as described in the text of Volume II. A new paradigm shift is required that incorporates the evaluation of the reward system, incentive-based learning, and procedural learning systems because these systems, which are underpinnings of cognitive control undergo significant changes between childhood and adulthood. In addition, this paradigm shift needs to include interpreting neuropsychological test performances within the context of what is currently known about the functions of the seven reliably identified large scale brain systems. The traditional and artificial "domain of cognition" approach no longer "works." The new variables of interest are the systems and networks themselves.

Decision Making and Anticipation

Volume II opened with a discussion of decision-making. Problem-solving was defined as a process of determining the stimulus-based properties of the circumstances requiring making a decision, and the actual decision was always based upon the anticipation of an outcome. The anticipation of the outcome was associated with reward value. Recent evidence demonstrates that decision making in adult populations is characterized by age-related changes. Although this might initially be interpreted as a frivolous finding, the factors that govern these age-related changes are the variables of interest.

When a decision needs to be made, in an ambiguous situation with unexpected or unpredictable reward outcomes, young adults explore the structure of the situation; they search for the stimulus-based characteristics of the problem. However, older adults do not think in this fashion; in fact, in experimental conditions, they perseverate. These differences in thinking and behavior were interpreted by concluding older adults have deficits in representing, or imagining and updating anticipated reward value, although this process is not necessarily a function of "working memory," dependent of course on how this term is defined [322]. Also, in younger adults, higher working memory capacity was associated with anticipating more distinct reward probabilities. This makes intuitive sense. However, in older adults, working memory capacity had no effect; even decline in working memory capacity did not predict perseverative choices or decision-making behavior. Instead, based upon fMRI findings, it was argued that a lack of recruitment of the lateral prefrontal cortex represented a manifestation of an inability to integrate expected reward value with decision making. The importance of reviewing these findings concerns the role of anticipation in decision-making behavior. Anticipation, described in this current volume as an inherent design characteristic of the brain, must be integrated with an understanding of the stimulus-based controls, or evaluation of the situation, in order to make appropriate decisions. In fact, a study of Parkinson's patients did not reveal a global decision-making impairment. Therefore, the Parkinsonian brain can continue to "anticipate." Instead, the evaluation stage, or the difficulty in identifying stimulus-based controls and associating these with possible outcomes was interpreted as interfering with the novel decision-making process [323]. Therefore, anticipation appears to always represent a key variable in cognitive control. Anticipation, associated with reward value, appear to represent the expansion of the cerebro-cerebellar and cortico-striatal systems as the critical underpinning of the cognitive control system. The continued operations and cooperation of these two vertically organized vertebrate brain networks seem to govern novel decision-making across the lifespan.

Problem-Solving, Procedural Learning, Automaticity, and Cognitive Control

This addendum opened by briefly reviewing a model of cognitive control that recognized a limited role of certain subcortical structures and implicit processes in decision making. However, according to that model [306], the cortex was also presented as providing modulation, or top down "sensitivity control" over underlying subcortical, implicit inputs. In the text of Volume II, it was clearly described that the prefrontal cortex and the basal ganglia interact to select or "gate" attention and behavior "candidates." However, the fact that all of the sensory and motor information is stored in the same distributed brain regions that were initially activated when a behavior was first learned was also reviewed. These sensorimotor characteristics are the task-relevant "representations" of thoughts and activities. It was also emphasized that all attentional selections and decision making are not under the top-down control of the prefrontal cortex. Considerable learning and decision-making are implicit processes and functions, outside of conscious awareness. Although the basal ganglia guide attention and behavior by focally releasing inhibition of task-relevant "representations," allowing the activity of appropriate cortical regions to be amplified, the basal ganglia are at the same time continuing to inhibit task-irrelevant "representations" or attentional and behavioral candidates. In other words, the basal ganglia simultaneously, actively inhibit other cortical regions. "Sensitivity control" over underlying subcortical inputs are "top down" when "candidate representations" are explicitly, volitionally chosen. However, even this control requires continuous "bottom-up" input. Simply put, it is not a "one way street." The inhibition of "unattended" sensory, motor, emotional, and motivational influences is an active, ongoing process. It is under the constantly active "default mode" control subserved by the basal ganglia [324]. This emphasizes another neuropsychological failure in identifying and characterizing the "stimulus-based properties" of the umbrella term of EF.

When the operations of the medial temporal lobe memory system were identified, characterized, and understood as supporting declarative (semantic and episodic) memory, numerous well-known investigations generated the conclusion that procedural and declarative memory systems did not interact. This assumption became generally accepted knowledge. That viewpoint was challenged. A tentative and provisional argument was proposed in Volume II (as well as in previous manuscripts cited within the text), emphasizing procedural learning can actually lead to the development of declarative knowledge. In fact, the interactions of these two learning systems was considered critical to development in children and an essential component of cognitive control. In support of this proposal, Paul and Ashby [325] demonstrated how the explicit system, which includes cognitive guidance, "bootstraps" learning early on in the procedural system. In fact, it was proposed that the procedural system first learns a suboptimal strategy employed by the explicit system. The procedural system then refines this strategy. This initial bootstrapping occurs through fronto-striatal interactions. This does not explain how procedural learning can generate declarative knowledge; explanations and examples of this "opposite end" of the process were already discussed within the original text of this Volume. However, this recently proposed explicit-implicit interaction is quite consistent with the novelty-routinization principle presented in Volume II, and very clearly supports the stages of sensorimotor learning which were presented as an ongoing process. The "two-way" street of explicit-implicit learning system interactions is a fundamental property of cognitive control. These interactions support the alternating episodes of automatic behavior with cognitive guidance necessary for adaptive behavior.

Epilogue or Epitaph: Personal Reflections, Viewpoints, and Considerations

The example I am about to offer will initially seem strange to the reader. Upon first reading, it might seem humorous, as if it didn't belong in a manuscript about neuropsychology. In that case, I have at least brought a chuckle to your day. Perhaps the example will only provide a review of an interesting but tragic story. However, if there is a lesson to be learned, it might not be out of context at all. It just might have an impact on every practitioner of clinical neuropsychology.

The RMS Titanic was considered an unsinkable ship. It had all sorts of safety features. It was the largest cruise ship of its time. It had the capacity for transporting over 3,000 people. However, on its maiden voyage, an unanticipated event caused something to go terribly wrong. The lack of recognition of a seemingly "minor" engineering design flaw, coupled with a glancing collision with an iceberg, generated an unbelievable catastrophe. A relatively small gash in the vessel's hull caused the ship to flood with water, break apart, and sink to the bottom of the Atlantic Ocean in less than 3 h. What was once taken for granted, unimaginable and impossible very quickly became a reality. You might conclude this story is of absolutely no relevance to this ebook series. My opinion is quite the contrary. I believe this example couldn't be more relevant.

Life has taught me that subtle communication often does not work. Sometimes a person has to be very direct. So, to be blunt, I equate the field of the clinical practice of neuropsychology to the Titanic, and the clinical practitioners are the passengers. The more optimistic reader might view advances within the neurosciences as constructive; this conclusion is exactly right, which is the point of my example. I participated in this ebook series to help bridge the gap between traditional neuropsychology and current neuroscientific thinking. One purpose of this ebook series is to update clinical practitioners by reviewing neuroscientific findings; another purpose calls for a paradigm shift in neuropsychological thinking. Hopefully, the reader will obtain useful, updated information and acquire a deeper understanding of the principles of brain-behavior relationships. So what are my questions and concerns?

Let's take a good look at clinical practice. When was the last time a new paradigm, based upon neuroscientific findings, was incorporated into clinical neuropsychological assessment? In my 35 years of practice, the primary change I witnessed was the introduction of learning and memory tests. Patients with hippocampal damage, coupled with investigations of primates as subjects, enabled an understanding of how the medial temporal lobe memory system operates. Some tests that were derived from these findings have proven extremely useful. Usually, a memory assessment is included in every neuropsychological evaluation, and this is a significant improvement in the assessment process. Unfortunately, some tests of learning and memory were developed, and continue to be revised, from an a-theoretical underpinning. Of what use is any test that does not directly tie theory to practice? Of what use is a revision of any test that has no known neuroanatomical substrate? In neuropsychology, sometimes we become preoccupied with the idea that "newer" means "better." But is this really the case? Of course not. If you don't know what you are measuring, why measure it? You are merely gathering uninterpretable data.

The brain can be thought of as made-up of multiple memory systems. One of these is the critically important procedural learning system, which can of course be subdivided into subsystems, and perhaps grouped under the general category of "non-declarative memory." A significant amount of information has been learned about these systems through experimental investigation. However, I am forced to ask myself the question of why an assessment of these systems has never been incorporated into practical neuropsychological evaluation? How much relevant clinical information about patients is being missed by overlooking these information processing and learning systems? These learning systems were described as playing critically important roles in the model of brain-behavior relationships presented in this series. We were all taught that "practice effect" is a potential source of error because this masks a person's "true" ability level. But aren't aspects of procedural learning essentially "practice effect" that reflects a person's learning capacities or aspects of ability level? If a person benefits from interacting with a test, doesn't this provide information about learning and adaptation? The answer to this question of why non-declarative learning and memory capacities are not included in assessment clearly does not lie in the "recency" of neuroscientific findings. Much of this information has been available for a considerable amount of time. I have also advocated for routinely evaluating the reward circuitry systems. Probabilistic category learning tests used in experimental studies have been around for a very long time. How come the field has not been able to directly apply these types of tests into clinical evaluation? Although a couple of tests of this type have been introduced, they always seem to include the idiosyncratic introduction of cognitive mediation to assist in task performance. This addition is exactly what needs to be avoided! I have heard the argument that such cognitive mediation can never be avoided in the development of these types of tests. Anyone thoroughly familiar with the literature can refer to studies that assess reward preferences while by-passing cognitive control, or "thinking."

Another lame excuse I have heard concerns the amount of time it would take to develop norms for the clinical application of these tests. Again, to be as blunt as possible, I see this as a flimsy rationalization. The truth of the matter is that the field of clinical neuropsychology does not control its own profession and destiny. It sits back and waits for test publishers to develop and sell assessment tools.

The field is not unified, and as a result, it has not been able to develop a mechanism for incorporating relevant neuroscientific findings into the assessment process. The field has failed to set standards of practice. In fact, in some ways, the field works against itself. There are all sorts of rules and principles of "ethical standards" that make it difficult for even the well informed practitioner to apply relevant findings to clinical practice. The field "ties its hands behind its back."

I am not saying that "norms" are not necessary. I am not concluding that "norms" are not useful. However, most of current test interpretation seems to be oversimplified and based upon a simple "level of performance" principle in which a test score is compared to a defined group population. However, this principle never explains the reason for that level of performance; it merely compares a person's test performance to a group of other people, which says nothing about symptom identification. How can an examiner identify anterograde amnesia by group comparison methodology? This identification requires the person to act as his or her own "control". For example, what was learned at baseline needs to be compared to what was remembered in a delayed condition, after the passage of time. This has nothing to do with a level of performance group norm. This individual comparison standard is a specialized instance of pattern analysis interpretation methodology, in which certain skill sets are compared to other skills within the same subject. And whatever happened to the notion of pathognomonic signs? This interpretative methodology informs us that when an aberrant behavior is observed, it points to pathology in each and every instance. This is the type of methodology relied upon in the neurological examination, a primary example being the finger-to-nose test. The fact that failure is identified immediately points to dysfunction. This methodology does not need a "group norm." Similarly, it does not need a "revision."

These interpretive methodologies need to be revisited in the field of neuropsychology. They should be included in setting standards of practice. In addition, developments in neuropsychological testing need to follow the same paradigms used in neuroimaging studies. Paradigm modification can easily recruit different brain systems, which can generate misleading test interpretation. Neuropsychological tests have been successfully used in characterizing brain-behavior relationships in an extremely wide range of neuroimaging studies. And, these studies are relatively brief and clearly demonstrate that diagnostically relevant information can be obtained in a relatively brief period of time. This idea is critically important. We are practicing neuropsychology within the context of a changing health care delivery system. Health care is expensive. Diagnostic testing is expensive. Simply put, the handwriting is "on the wall." There is no more room for the luxury of administering a lengthy neuropsychological evaluation while using tests that are a-theoretical and do not directly tie neuroscientific theory to practice. Anyone who believes that the lengthy assessment process is required to generate useful diagnostic information is a "passenger" on the Titanic, perhaps ordering a meal in the main dining room as the ship goes down by the bow.

This series offers the practitioner a "lifeboat." Neuroscience has reliably identified functional brain networks. Although much remains to be discovered, information is available about how these brain systems develop and about how large scale brain networks interact in both health and "disease." Significant information is known about how these brain networks interact with two fundamental vertically organized brain systems that include the basal ganglia and cerebellum as major components of cognitive control. These "systems" are here to stay. Neuroscience will learn considerably more about these network interactions in the future. This information will modify the current "interim solution" about our understanding of brain-behavior relationships. However, the seven presently known large scale brain systems should be the only accepted standard reference points for interpreting neuropsychological tests. Certain existing neuropsychological tests can already be interpreted within this framework. However, other tasks that have been successfully used in neuroimaging studies that have assisted in our understanding these network operations also need to be employed. I, along with a small handful of colleagues, are taking affirmative action in developing tests that are necessary for clinically evaluating these complex brain networks. It seems odd that all of us are clinical practitioners, without external sources of funding. Perhaps this speaks towards a disconnect between the worlds of academia, research, and clinical practice.

During my clinical training, I was taught that any set of test results can be subject to either false positive or false negative error. Because each type of error carries different implications for different patients in different situations, I was also taught how to evaluate the possible outcomes of making false positive and false negative errors. Thinking about these possible error outcomes can assist in the diagnostic decision-making process. Many readers might disagree with my views about the status of neuropsychological evaluation and believe my perspective is a false positive error. However, I have absolutely no problem in accepting the responsibility that I am making a false positive error in my conclusions about the field of neuropsychological evaluation. I am still promoting a viewpoint that can only help move the field forward, while completely avoiding the risk of false negative error and its likely, or perhaps even inevitable outcome.

Sometimes when I read a paper about brain-behavior relationships I am immediately struck by nature's neurobiologic consistency. I am reminded that a species that adapts to change survives, and that those that don't become extinct. I then sit back and wonder how this evolutionary principle might apply to the field of clinical neuropsychology.

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