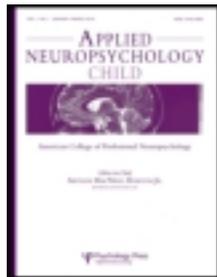


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From Movement to Thought: The Development of Executive Function

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From Movement to Thought: The Development of Executive Function

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This article presents a very simple definition of executive functioning (EF). Although EF is traditionally understood as a cognitive function dependent upon top-down cortical control, we challenge this model. We propose that the functional architecture of the brain evolved to meet the needs of interactive behavior and that cognition develops to control the motor system, which is of paramount importance in adaptation, essentially a manifestation of EF. We propose that traditional models of cognition are incomplete characterizations of EF and that procedural learning and “automatic” behaviors are the most basic, bottom-up functions that support all EF. We propose that motor development in children demonstrates how all knowledge is grounded in sensorimotor interaction and how interactive behavior generates both procedural and declarative knowledge, which later interact to generate EF. This model emphasizes the critical importance of motor behavior in children and stresses the importance of the pediatric motor examination in understanding the development of EF. This model also has implications for why traditional tests of EF have little predictive validity in both children and adults.

Key words: executive function, neurodevelopment of cognition, procedural learning and EF

INTRODUCTION

There is no consensus or universal agreement concerning the definition of executive function (EF). Barkley (2012) and Wasserman and Wasserman (2012) identified at least 18 definitions of EF that include varying skills and abilities. In this article, EF is defined in a very simple way—as *the functions an organism employs to act independently in its own best interest as a whole, at any point in time, for the purpose of survival*, as initially proposed by Miller (2008) and elaborated upon by others (Ito, 1997; Koziol, Budding, & Chidekel, 2012). However, EF is often evaluated through a serial-order information-processing paradigm. Within this model, first we perceive, then we think

to formulate a response, and finally we act. Most neuropsychological tests of EF have been based upon and developed from this assumption, even though there is little evidence to support this model (Cisek & Kalaska, 2010). Nonhuman primates, and people, are not usually functioning within the “perception–thought–action” serial-order processing paradigm. A primate in its natural habitat is obviously not performing an artificial experimental task within a university laboratory; a person is typically not performing a letter–number sequencing task or thinking about how to solve a Wisconsin Card-Sorting Test (Berg, 1948; Grant & Berg, 1948) or Tower of London/Hanoi Test (Shallice, 1982) unless they are participating in a cognitive evaluation. On a day-to-day basis, children and adults are almost always doing something; we are constantly interacting with the objects and people in the world in “real time” as situations unfold in very practical ways. This interactive paradigm is one of

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the critical underpinnings for why neuropsychological tests can have such difficulty in predicting “real-life” behaviors that require “EF” and why observational behavioral rating scales can have much greater ecological validity (Barkley & Murphy, 2010; Wasserman & Wasserman, 2013).

EF is often considered to be mediated by the prefrontal cortex (PFC) and/or prefrontal–parietal-lobe interactions (Fuster, 2008). Broadly speaking, however, goal-directed behavior requires the functional integration of distal brain regions (Wong & Stevens, 2012). This refers to transient, dynamic, context-specific interactions that convey information through subsets of anatomical connections among certain circumscribed brain areas that are engaged by a particular cognitive/behavioral process (Koziol & Stevens, 2012). These networks often include the involvement of subcortical structures (Koziol & Budding, 2009; McNab & Klingberg, 2008). In this regard, behavior is driven by large-scale brain networks (Castellanos & Proal, 2012). These regional brain interactions change during the course of development (Casey, Tottenham, Liston, & Durston, 2005; Chu-Shore et al., 2010; Shaw, Gogtay, & Rapaport, 2010). One very clear, obvious difference between adults and children is that they think about different things, in different ways, and they have a different behavioral repertoire (Cepeda & Munakata, 2007; Chatham, Frank, & Munakata, 2009; Snyder & Munakata, 2010). In clinical neuropsychological assessment, however, both adults and children are often mistakenly evaluated almost as if they were the same. A child is often misunderstood as a “smaller version” of an adult. For example, children are frequently administered easier, “watered down” versions of the same tests that are given to adults (Baron, 2004). Test performances at different ages are usually interpreted as if they were generated by the exact same brain regions. Different processes, however, drive cognition and behavior at different ages (Blakemore & Robbins, 2012).

In this regard, the field of clinical neuropsychology has also been constrained by a corticocentric model of behavior. Most of us are taught that the variables of primary interest in neuropsychology and cognition are mediated by the functions of the neocortex. This is a “top-down” approach for understanding thinking and behavior that fails to consider the critical contributions of phylogenetically older subcortical structures of the brain such as the basal ganglia and the cerebellum (Arsalidou, Duerden, & Taylor, 2012; Ito, 1993; Koziol & Budding, 2009; Koziol, Budding, & Chidekel, 2010). This top-down model seems to be at odds with the well-accepted developmental concept that development occurs from proximal to distal regions, rather than the other way around as the corticocentric model implies (Fair et al., 2007; Kolb & Whishaw, 2008; Supekar, Musen, & Menon, 2009).

This article places a very simple definition of EF within a phylogenetic, neurodevelopmental, and integrated model of brain functioning. This interactive model emphasizes *action control* instead of focusing upon *thinking* as a primary driver of behavior. This article proposes that cognition and EF evolved from the development of the motor system to control it, and in this way, there is no critical difference or “duality” between motor and “cognitive functions” (Bloedel & Bracha, 1997). The brain’s functional architecture evolved and develops from childhood to adulthood to meet the needs of interactive behavior. The brain’s fundamental organization can be interpreted as based upon the need for action control instead of thinking.

THE NECESSITY OF A DUAL-TIERED MODEL OF FUNCTIONING

Most of what we do in life is “automatic.” We do most things spontaneously, outside of conscious awareness, simply because these things need to be done. It is estimated that 95% of adult human activity, almost everything we do, is of this routine type (Bargh, 1997; Bargh & Chartrand, 1999; Lakoff & Johnson, 1999). These behaviors are efficient, elegant, and initiated without hesitation; these behaviors are adaptive and adjustable to contextual changes (Imamizu & Kawato, 2009; Saling & Phillips, 2007). We are not “born” with these behaviors. Children must learn these behaviors. Once these behaviors are learned, they are executed without giving the situation a second thought. These behaviors reveal the significant role that implicit processes play in EF because these behaviors are necessary for survival. Automaticity is not *optional*; instead, *automaticity is an absolute necessity*. Without it, almost everything we do would be experienced as “doing it for the first time” because cognitive control would always be required.

During the course of the day, however, events do not always go as well or as smoothly as expected. We may be confronted with situations we did not expect; we may be faced with novelty. At these times, previously learned behaviors that have become automatic no longer work, and additional adaptive control processes must be recruited to meet the demands of situations. Sometimes an adaptive response does not require much thinking and the behavior needs only minor adjustment, but many times, the novel nature of the situation requires us to “figure out what to do” on our own, independently. We need to stop what we are doing to devise a different response and make a different decision. This type of responding requires higher-order cognitive control. The resultant behavior can also be termed a manifestation of EF as well, and this is arguably the type of process required in a serial-order processing paradigm upon

which many neuropsychological tests of EF problem-solving are based. This type of responding that is based on higher-order control is, however, insufficient for adaptive functioning. It has a critical drawback. This type of process operates slowly and does not allow behavior to occur in “real time” (Toates, 2005). For any given novel situation, if the behavior is repeated, it can become an automatic response; this is important because it conserves cognitive resources after the behavior is learned. New “procedures” can be acquired and subsequently automated for future application quickly and without necessarily thinking about them.

During the course of “online” daily living, a person is interacting with an environment that requires alternating episodes of automatic behavior and higher-order control. This is the heart of adaptation and overall “EF.” Both systems of functioning are absolutely necessary. A person cannot survive with only one or the other. If a person’s behavioral repertoire consisted only of “automatic” responses to either internal or external stimuli, behavior is reduced to *reactive* context processing, responding to only external or internal stimulus necessities; this precludes or obviates voluntary, purposive, goal-directed, planned behaviors, which lie outside the here-and-now and actually must override the situational characteristics of the present. On the other hand, if the behavioral repertoire consists only of *proactive* higher-order control, then behavior unfolds too slowly and cannot occur in “real time.” (A comprehensive description of the advantages/disadvantages of stimulus-based processing vs. higher-order control is beyond the scope of this article; for a useful review, see Toates, 2005). Therefore, both processes are absolutely necessary to adapt to the changing characteristics of the sensorimotor environment within which we live (Koziol & Budding, 2009; Koziol, Budding, & Chidekel, 2010).

SOLVING THE PROBLEM OF SLOW INFORMATION PROCESSING

The serial-order processing paradigm, described as the model based upon “*perceive–think–act*,” relies upon direct sensorimotor feedback. This level of processing is slow because it is delayed by a variety of factors, some of which include the time required for processing basic and/or complex sensory information and the delay for the transmission of motor commands from the brain to the muscles, not to mention the processes of thinking and organizing motor responses (Imamizu, 2010; Shadmehr, Smith, & Krakauer, 2010). So, how might a brain develop to meet rapidly changing, emerging demands for survival while immediately interacting with the environment and also allowing for choices and decisions based upon longer-term interests and goals that go well beyond the

demands of the present? What type of solution would allow for both *reactive* and *proactive* context processing while resolving the issue of slow information processing? The polarity or contradictory demands of these issues presented nature with a perplexing problem. The answer appears to lie in evolution’s ability to develop mechanisms for *anticipation* to guide the activity and movement necessary for survival. (This will be discussed in the section titled, “The Role of the Cerebellum.”)

INTERACTIVE BEHAVIOR VERSUS THINKING

The functional architecture of the brain evolved and developed to meet the needs of interactive behavior and *not* to meet the requirements of thinking (Stout, 2010). In this regard, neural processing is continuous; it is ongoing as noted by the fact we are almost always “doing something.” Within this interactive process, all of the important, salient properties and characteristics of objects, such as what they are and look like and what they are used for, are represented and retained within the same *sensory* and *motor* brain circuits that were initially activated when the information about that object was initially encountered or first acquired (Freeman & Ambady, 2011; Freeman, Dale, & Farmer, 2011; Hendriks-Jansen, 1996; Martin, 2007; Valyear, Chapman, Gallivan, Mark, & Culham, 2011). These “sensorimotor circuits” can be referred to as cerebrocortical control models; Heilman and Rothi (2003) refer to these models as praxicons (sensory parameters for motor functioning) and innervatory programs (motor programs), while Ito (2011) refers to these as body and motor schemas. These circuits operate as an *ensemble*.

This information-processing system can be broken down into two divisions. The ventral pathway, anchored within occipital–temporal-lobe connections, was initially conceived of as an object identification or “what” pathway, while the dorsal stream, anchored within occipital–parietal-lobe circuitry, was conventionally considered as the object location or “where” pathway (Blumenfeld, 2010). The ventral pathway, however, has extensive connections with reward centers of the basal ganglia and regions of the PFC that predict or anticipate reward expectancies and outcomes (Boorman & Noonan, 2011; Doll & Frank, 2009; Haber, 2011; Heekeren et al., 2007; Sallet et al., 2011; Sheth, Abuelem, Gale, & Eskandar, 2011). As a result, this information-processing stream “knows” about reward value associated with object identity; it therefore biases potential actions. The dorsal stream is concerned about “spatial” information because it not only registers where something is, but also “how to do” something, while specifying the parameters for action; for a simple example, an object’s shape, size, and movement, which is sensory information processed within

the dorsal pathway, provides the premotor cortex with the information it needs for developing and executing the appropriate movements for grasping. These two sensory information-processing pathways project sensory information to frontal systems for the purpose of action choice and execution. In addition, the ventral and dorsal streams are integrated by the age of 9 months through callosal and regional hippocampal connections (Njiokiktjien, 2010), which is a critically important fact when considered from a neurodevelopmental, pediatric perspective.

Cortical-basal ganglia (reward center) interactions process “reward probabilities,” information about both positive and negative rewards, based upon experience (i.e., prior positive and negative outcomes of behaviors). With repetition, the appropriate context-specific sensory cortex and motor regions co-activate, and the strength of these sensory-motor circuits increases. In this way, the cortex acquires automatic behaviors for situations based upon the probability of having selected these actions in the past for the given context (Cockburn & Frank, 2011). Activation of the direct pathway of the basal ganglia allows the cortex to learn what it should do; activation of the indirect pathway allows the cortex to learn what it should not do dependent upon the given stimulus contexts. Activation of the hyperdirect pathway of the basal ganglia puts an immediate stop to behavior in those contexts where a different or “new” behavior needs to be thought about, chosen, or developed (Cockburn & Frank; Doll & Frank, 2009; Frank, Samanta, Moustafa, & Sherman, 2007). (This article assumes the reader is familiar with the functional neuroanatomy of the basal ganglia. A full description of the function of the basal ganglia and reward circuitry systems is beyond the scope of this article. The unfamiliar reader is referred to Doll & Frank, and Utter & Basso, 2008, for informative reviews).

According to this interactive model, which has been proposed by Cisek and Kalaska (2010) and others (Koziol, Budding, & Chidekel, 2011), several different potential actions are available in most situations. These choices, decisions, and activities are represented across large regions of the cerebral cortex and involve large-scale brain systems and networks. Central to this model is the fact that decision making is not strictly localized within the PFC; it is “localized” within the distributed brain networks that are responsible for processing sensory information, associating that sensory information with reward valence, and programming and executing the required actions. Cognition is not separate from sensorimotor control in this paradigm; in fact, as behaviors become automatic, conscious cognitive control becomes subordinate to “automatic” behavior. Therefore, the “EF” that is necessary for survival has a changing locus of control that does not appear to be captured by neuropsychological test paradigms for the assessment of EF. This model is schematically illustrated in Figure 1.

THE ROLE OF THE CEREBELLUM

Although this summary is oversimplified, the role of the cerebellum is to assist with automaticity by adapting behavior to the current context. The cerebellum serves this function through the development of cerebellar control models (Ito, 2011). As indicated earlier, behavior that is dependent upon direct sensory feedback unfolds too slowly. Broadly speaking, the cerebellum functions as a predictor or anticipator of this feedback. When acquiring a new behavior, the initial learning trials do rely upon external sensory feedback, as described by Ito (2011). However, the cerebellum “copies” the content of cortical working memory, which includes the “praxicons” and “innervatory programs,” or “body schema” and “motor schema,” necessary for the performance of the task (see the section titled, “Solving the Problem of Slow Information Processing”). Therefore, the control model constructed by the cerebellum includes the dynamic sensory and motor features and processes necessary to perform the behavior. This internal model is recalibrated or adjusted as the movement is repeated so that the movement becomes more and more precise. Behavior becomes more efficient, faster, and automatic as it is repeated because the cerebellum learns to *predict* this feedback. By transmitting refined neural signals about this anticipated feedback back to the cortex, the brain is able to execute the movement/behavior with increasing precision, without the need to refer to feedback from the moving body part. In a sense, the cerebellum teaches or instructs the cerebral cortex to perform skillful, precise, automatic behaviors, outside of conscious awareness, by *anticipating* movement outcomes (Blakemore & Sirigu, 2003; Doyon et al., 2002; Galea, Vazquez, Pasricha, Orban de Xivry, & Celnik, 2010; Houk et al., 2007). The cerebro-cerebellar circuitry system features segregated, reciprocal connections from nearly all regions of the cerebral cortex. This circuitry system is schematically depicted in Figure 2. The cerebellum performs a similar operation on all sensory, affective, cognitive, and motor information, allowing functions within these domains to operate smoothly, efficiently, and effortlessly outside of conscious awareness while appropriately adapting these functions to contextual changes. Important to this discussion is the principle that what the cerebellum does for movement, it does for thought; for example, while the cerebellum teaches the frontal lobes to anticipate movement outcomes and to guide behavior on that basis, it similarly teaches the PFC to predict or anticipate thought outcomes, which are essentially the planning and organizational functions of the PFC, which are the functions inherent in traditional concepts of EF. The cerebellum teaches the PFC how to “think ahead.” A simplified example of this circuitry profile is illustrated in Figure 3. (A comprehensive presentation of cerebro-cerebellar circuitry profiles and control models is beyond the scope of this article; the

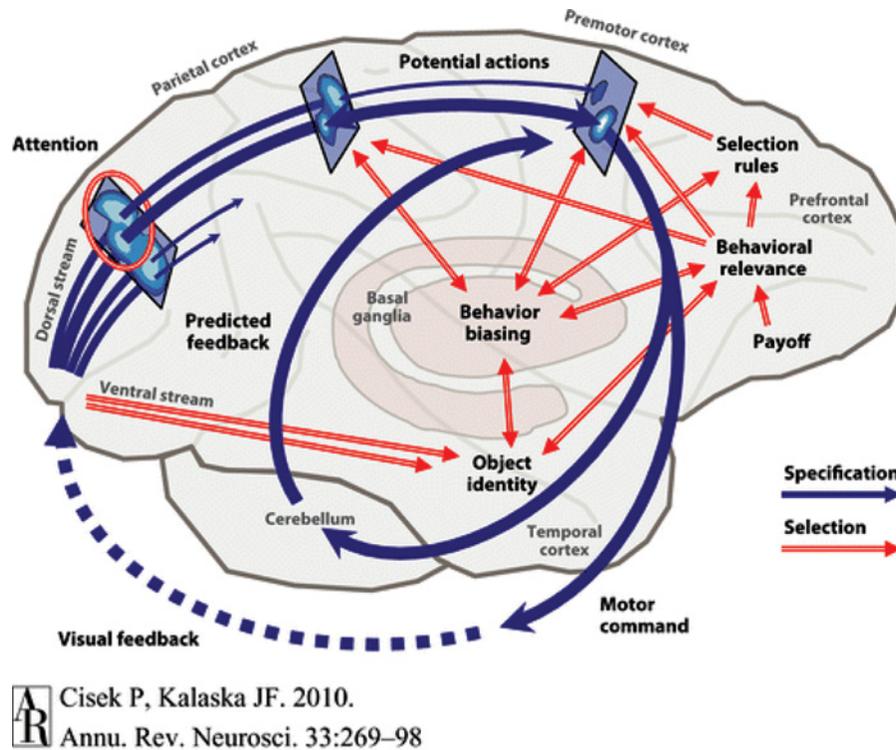


FIGURE 1 This diagram represents a sensorimotor interaction paradigm for visually guided movement and illustrates interactions between the cortex, basal ganglia, and cerebellum. The dorsal stream, which consists of the parietal cortex and reciprocal connections with premotor regions, is concerned with 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 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 serves object identity. (Connections with dorsal stream 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 the cerebral cortex and the 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 internal anticipated or predictive feedback, which are inherent in cerebellar control models—not illustrated in this diagram—and are the subject of the remainder of this article. Reprinted with permission. (Color figure available online.)

interested reader is referred to Ito, 2011; Koziol et al., 2011, 2012; and Schmahmann, 1997, for reviews).

Therefore, nature developed predictive mechanisms for *action control* and not for the purpose of *thinking* per se. Reactive context processing and/or procedural (skill) knowledge can be explained and understood in terms of continuous “online” sensorimotor anticipation. The brain developed mechanisms to control action, or behavior, by anticipating sensorimotor outcomes while continuously interacting with the environment. This essentially bypasses the need for direct sensorimotor feedback. New associations/behaviors can be acquired through repetition, and when automated, can be released quickly and precisely to meet the needs of adaptation. When these motor skills and procedures are *simulated or imagined* (i.e., when reflected upon or thought about offline), however, it can result in the development of semantic, declarative knowledge that could be used later for proactive behaviors—in other words, the decision making and

guidance or control inherent in what is traditionally known as “EF.” In this way, both procedural and declarative knowledge can be thought of as grounded in sensorimotor anticipation (Pezzulo, 2011; Weber & Vosgerau, 2011).

Pezzulo (2011) gives several examples to illustrate these anticipatory control mechanisms. For instance, consider the mechanic who is working on the maintenance of an engine. Through “online” training with the “hands-on” experience of working on the engine, the mechanic can learn to disassemble and reassemble that engine “in his head,” running an “offline” simulation of the process. The cognitive reenactment of this process can lead to the development of declarative knowledge. In other words, the acquisition of a *procedure* (learning how to assemble an engine) has generated *declarative, semantic* information, which can be thought about and talked about, without necessarily engaging in the activity. Before performing maintenance on the engine, the mechanic can reuse that information to plan the work of

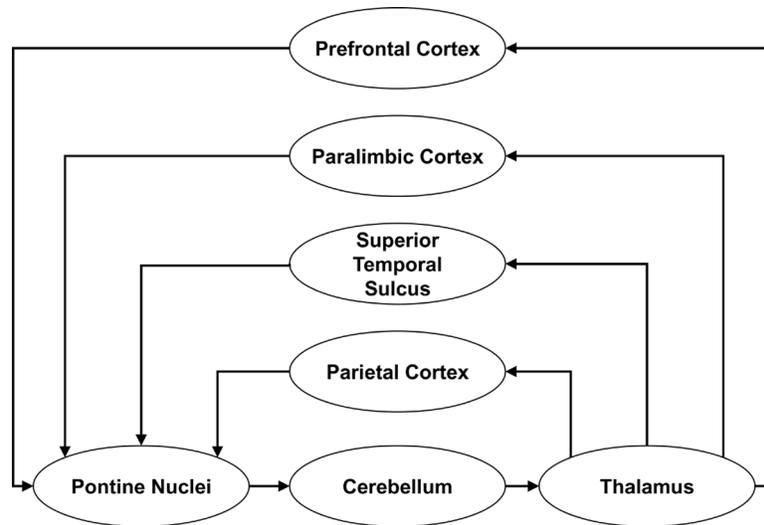


FIGURE 2 Connections between the cerebellum and the neocortex.

engine maintenance; similarly, that information can be *manipulated*, perhaps in a different sequence, to theoretically plan how to make an improved engine. The example of the interior decorator is also offered. The designer can compare all sorts of furniture arrangements and color schemes in a room, while additionally anticipating or predicting whether or not the customer will be satisfied. These kinds of manipulations are “EF,” including social-skill “EF,” with the only difference being imagining or simulating the activity instead of actually engaging in the activity. Movement, activity, and imaging that literally share the same neural substrates (Guillot, Di Rienzo, MacIntyre, Moran, & Collet, 2012).

There is compelling evidence that thinking about or planning the use of an object activates the same brain regions that were recruited when that object was actually used, and that thinking about the execution of an activity can actually improve the later performance of that activity (Hotz-Boendermaker, Hepp-Reymond, Curt, & Kollias, 2011; Jeannerod, 2001; Johnson-Frey, Newman-Norland, & Grafton, 2005; Miall, 2003; Wadsworth & Kana, 2011). Therefore, procedural learning can lead to declarative knowledge, and declarative information can be imagined to facilitate procedural activity. In this way, cognition, or EF, controls the motor system, while movement and thought can be considered equivalent. This is

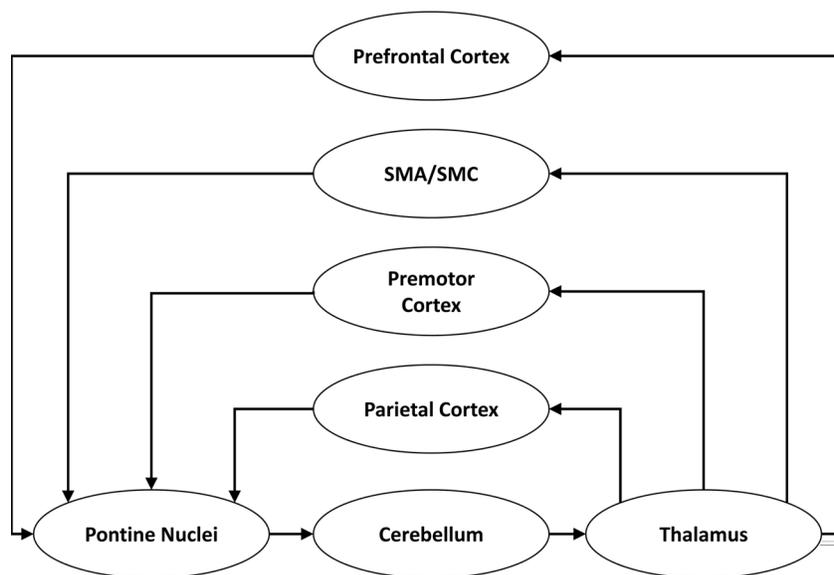


FIGURE 3 Schematic illustration of cerebellar-parietal-frontal lobe connections.

very consistent with Ito's well-established proposal that movement and thought are equivalent control objects for the cerebellum; when a movement or a thought is coded within the cerebellum's circuitry system, the control and manipulation of the body limb involved is no different than the control and manipulation of thought content (Ito, 1993, 2008). This also helps explain how we move in complex ways without being consciously aware we are doing so, while similarly, we are most frequently unaware when we are actually thinking; as stated by Ito (2005, p. 101), "the events of the cerebellum are not reflected in consciousness."

THE DEVELOPMENT OF LARGE-SCALE BRAIN NETWORKS

The neonate does not enter the world with the skills to think or with cognition; nor do they enter the world with procedural or declarative memories. These must be acquired. Instead, the infant enters the world with movement. As summarized by Casey and colleagues (2005), the human brain undergoes significant changes in its structural architecture and functional organization during the course of development. All brain regions associated with sensory and motor processes and functions mature first. This starts to suggest the relationship of the control of movement and the development of EF. This is followed by maturation of association areas that presumably govern the top-down control of behavior. As reviewed by Tau and Peterson (2010), the functional domains of visual processing, attention, memory, and cognitive control rely on the development of distinct yet interconnected sets of anatomically distributed cortical and subcortical regions.

Mesulam (1990) was perhaps the first to propose that cognitive function was dependent upon the operations of five distinct, distributed large-scale brain networks. Menon and Uddin (2010) cited examples of how unexpected aspects of a brain network, such as the insula, can play a critical role in cognitive function such as salience detection, attention, and cognitive control. More recently, Yeo and colleagues (2011) identified the remarkable replicability of seven major, large-scale functional connectivity profiles in 1,000 adult normal control subjects. These networks include the visual, ventral, dorsal, frontal-parietal, and limbic-basal ganglia networks described earlier (because functional descriptions of all of these networks is beyond the scope of this article, we have not described these networks in detail and we have omitted certain networks, including the default network; the interested reader is referred to Castellanos and Proal, 2012; and Yeo et al., for reviews). Habas et al. (2009) and Buckner, Krienen, Castellanos, Diaz, & Yeo (2011) have demonstrated how discrete, segregated, nonoverlapping

regions of the cerebellum connect to these functional connectivity profiles.

Because most studies of intrinsic connectivity networks have been conducted with adult subjects, the development of these large-scale functional brain networks is not completely understood. Within the cerebral cortex, the neurocognitive functions of attention, visual and auditory information processing, memory, and the cognitive control of working memory rely on the development of distinct yet interconnected sets of anatomically distributed cortical and subcortical brain regions. The organization of this circuitry is a complex developmental process that is influenced by genetic and hereditary predispositions, environmental events, perturbations, and experiences, all of which are also associated with numerous vulnerabilities (Tau & Peterson, 2010).

The emerging area of investigation that applies the techniques of network analysis to the developing brain has recently demonstrated that at each stage in normal neurodevelopment, age-specific skill sets correlate with age-specific distributed brain networks, which develop in a predictable way (Chu-Shore et al., 2011). Supekar et al. (2009) reported that children and young adults exhibited similar patterns of network organization at the global level. In children aged 7 to 9 years old, however, subcortical brain regions were more strongly connected with primary sensory, association, and paralimbic areas; young adults (19 to 22 years old) exhibited stronger cortico-cortical connectivity between limbic, paralimbic, and sensory association areas. When tracing white-matter tracts within functional connectivity profiles, the development of these large-scale brain networks is characterized by a *weakening* of short-range functional connectivity and a *strengthening* of long-range functional connectivity of more distal brain regions involved within networks. In a study that featured the development of control networks, adult control networks were characterized by a *decrease* in short-range connections and an *increase* in long-range, distal connections that comprise these networks (Fair et al., 2007). These studies imply *the changing internal locus of control of behavior during the course of development*, from "bottom-up" influence to the gradual development of "top-down" control. Therefore, the conclusion is offered that assessing cognitive function and EF in developing children is analogous to trying to evaluate a "moving target." This is another potential reason why traditional neuropsychological tests of EF might not have robust predictive, ecological validity.

MOVEMENT AND EF IN CHILDREN

Numerous researchers have described a relationship between movement and EF. These studies will not be

reviewed in this article (the interested reader is referred to Gibson, 2002; Piek, Dawson, Smith, & Gasson, 2008; Piek et al., 2004; Poore & Barlow, 2009; Roebbers & Kauer, 2009; and Westendorp, Hartman, Houwen, Smith, & Visscher, 2011, for specific findings and selective preliminary reviews). Instead, an example is offered to illustrate how sensorimotor interaction in childhood can generate procedural and semantic, declarative knowledge for the development of EF. This example was originally proposed by Koziol et al. (2011), and it is restated here because of its simplicity and practicality.

All children must learn to use and master silverware; this essentially means that children must learn to use tools, which are considered to be an extension of the limbs. This requires action control. Learning how to use spoons and forks is important because this process mimics the finger-to-nose test used in the neurologic examination; according to Ito (2011), this test is dependent upon a cerebellar control model. For example, in the finger-to-nose procedure, the subject cannot see their nose; its location must be *anticipated*. In the acquisition of silverware use, the child cannot see the mouth, and its location must similarly be *predicted*. In addition to recruiting the cerebellum, learning to use tools is heavily dependent upon the integrity of the dorsal stream of information processing that has been described in initial sections of this article. This circuitry system was characterized as a critical control system for action execution. This action control area is a large-scale brain network that consists of reciprocal premotor frontal region–parietal-lobe projections; connections between the parietal lobes and the frontal eye fields; connections between these regions and the cerebellum; frontal-cerebellar reciprocal connections; connections between the lateral posterior cerebellum with the parietal lobes and the superior temporal sulcus (Blakemore & Sirigu, 2003; Doron, Funk, & Glickstein, 2010; Krienen & Buckner, 2009; Njiokiktjien, 2010).

Most children use an adult-like, clenched grip for silverware near the time they are 3 years of age. This grip consists of the thumb pointing toward the head of the “tool,” although it is well recognized that a variety of grip patterns are used through experimentation before a grip preference is established (Adolph & Berger, 2006). When bringing food to the mouth, the movements for using a spoon and a fork are somewhat different; the grip and movement required for using a knife is different from the movements for using a spoon and fork, and to be sure, at least for safety reasons, knife use develops well after fundamental silverware use. Silverware use is initially very awkward; however, with practice or repetition and appropriate time, the typically developing child masters all the different grips and movements; both automaticity and flexibility are acquired. At this final level, this presumably reflects the functions of cerebellar control models

(Higuchi, Imamizu, & Kawato, 2007; Imamizu, 2010; Imamizu & Kawato, 2008; Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003). This tentative conclusion is based upon extrapolation from adult studies of tool use; there are no studies of this type conducted with children, so how cerebellar control models specifically develop in childhood remains unknown. In learning the *procedures* for using a spoon, fork, and knife, the child learns about the *semantic category* of silverware. The child also learns that a spoon serves a certain function for eating liquids, such as cereal or soup. The child learns that because a fork has prongs, it cannot serve the functions of a spoon, while because a spoon is rounded, it cannot serve the purpose of spearing meat or vegetables. A knife can spread or cut food that is located on a plate; however, it can also be used in other contexts, for cutting away from the table and for cutting other objects outside of the semantic category of food. Silverware use directly leads to knowledge about food texture as well. A spoon is used for liquid served in a bowl; to drink other liquids, such as milk or water, a cup is used, which requires a different grip and different movement than that of a spoon or fork. The content of the cup satisfies thirst; the content of the bowl/spoon satisfies hunger. Soup, cereal, meat, vegetables, milk, and juice are all within the semantic category of food. It is also learned, however, that these foods serve the satisfaction of different needs.

It is no accident that by the time a child reaches 3 years of age, at the ending phases of infantile amnesia and when association cortices start to mature, semantic associations are learned and retained (Hayne & Imuta, 2011; Piek et al., 2008). The child acquires semantic, declarative knowledge through the process of procedural learning. All of this knowledge has been acquired through the process of sensorimotor anticipation, inherent in the fundamental processes of eating and drinking. In this way, all knowledge, both procedural and declarative, is initially grounded in the process of anticipation, which is a fundamental design characteristic of the brain (Kinsbourne & Jordan, 2009). This process also represents the forerunner of the thinking that is required for EF. In other words, all of this “knowledge” stems from direct sensorimotor interaction with the environment, while demonstrating the relationships between movement, action control, and thinking, which is a process that develops from, and later controls, the motor system.

SUMMARY AND IMPLICATIONS

This article presented a dual-tiered model of behavior. This model featured the critical importance and necessity of both automatic and higher-order control behaviors operating cooperatively. EF was featured as a process that is evident at both general levels of behavior. The

assumption of a serial order-processing paradigm upon which neuropsychological tests of EF are developed was challenged. Instead, it was demonstrated that people function within an environment that demands almost constant interactive behavior. Both procedural and declarative knowledge can be acquired through this paradigm of sensorimotor interaction, which emphasizes the progressive development of motor, or *action control*. It was proposed that the brain develops to meet the needs of interactive behavior, and not for the primary purpose of thinking.

This model actually proposes three “executive systems.” The process of acquiring information through the instrumental learning reward system is one type of EF; the role of the cerebellum represents another type of EF because it assists in automation and in adjusting behaviors according to contextual changes; the cortical, top-down control system represents a third form of EF based upon cognitive control or thinking. Because the participation of all three brain regions is necessary for survival, however, these are all valid forms of EF, even though most of the behaviors generated by the interactions of these brain systems are outside of conscious cognitive awareness. This proposal is similar to the reinforcement learning module and to the supervised and unsupervised learning systems initially proposed by Doya (1999).

Tests of EF in children have been described as having little ecological validity (see Isquith, 2013). This is the case for a variety of reasons. First, the paradigm upon which these tests are based does not reflect the requirements of interactive behavior for adapting to the environment. The current neuropsychological testing paradigm for EF occurs approximately 5% of the time in the life of an adult (Bargh, 1997; Bargh & Chartrand, 1999; Lakoff & Johnson, 1999). A child acquires both procedural and semantic declarative information through directly interacting with the environment. This represents a very slow, protracted process that is characterized by a changing neuroanatomic underpinning. This neuroanatomic base concerns the development of large-scale brain networks. Just because a “watered-down” test of adult EF can be administered to pediatric populations does not mean that these cognitive functions are used to guide behavior. In fact, children are notoriously tied to the present in their behavior, often demonstrating a dissociation between “knowing” and “doing.” There is good anatomic evidence for this to be the case. For instance, behavior is dependent upon large-scale brain networks, which include the development of functional connectivity between distal brain regions. Although on a global level, children and adults were described as exhibiting similar patterns of brain network functional connectivity, at earlier ages, through at least 9 years of age, the strongest connections are within and between proximal brain regions. These proximal connections include cortical connections with

the reward system of the basal ganglia. In adults, studies of brain connectivity reveal that cognitive control is dependent upon the strengthening of connections between *distal* brain regions while proximal connections weaken. Based upon these neuroanatomical profiles, it should be no surprise that the behavior of children is often directly coupled with immediate situational salience and rewards, independent of the child’s level of factual, declarative knowledge. In fact, as has been demonstrated by Chatham et al. (2009), children make a very slow, gradual shift in behavioral control as brain systems slowly mature and develop, while during this course of early development, behavior is not guided by cognitive functions such as “working memory.”

The proposals of this article imply that neuropsychology needs to develop and adjust its tool kit for assessing EF according to the simple definition offered that requires a dual-tiered system of behavioral control. Tests of procedural learning in children are currently absent from the clinical psychologist’s tool kit. These tests could easily be added. For example, repeating the Trail-Making Tests over multiple trials would provide an index of procedural learning. Similarly, the older Wechsler Mazes, when administered over several trials, would provide an index of learning the “procedure” of solving the maze. Multiple administrations of these tasks have been avoided because of the concept of “practice effect,” which has been interpreted as a source of error in the measurement of cognitive functioning. Practice effect of this type, however, really involves the acquisition of new procedures, which is at the base of child development in acquiring control over the motor system. Traditional tests of EF, such as the varieties of different “tower” tests, could easily be adapted for a procedural learning paradigm. One way to accomplish this would be to repeat the same tower problem over and over again before administering the next problem in the series. The goal of this type of test administration would be to determine the length of time necessary to automate the procedure. Therefore, updating an approach to pediatric neuropsychological evaluation need not be far off on the horizon. Similarly, there are no commercially available tests for evaluating reward preferences, although these tests do exist within the experimental literature. In fact, certain probabilistic category-learning tests are constructed to make the subject almost constantly feel as if they are guessing, because abstract stimuli that cannot be cognitively conceptualized are typically employed, while providing either positive or negative “rewards” only a certain percentage of the time (Kasanova, Waltz, Strauss, Frank, & Gold, 2011; Waltz, Frank, Wiecki, & Gold, 2011). This approach clearly minimizes conscious cognitive control influences. Koziol and Budding (2009) have described how a variety of commercially available tests can be modified to meet the requirements of assessing interactive learning behaviors

while also describing the changing neuroanatomy of these tasks as they are mastered. Similarly, they have proposed, along with Koziol and Stevens (2012), that the clinical neuropsychologist's arsenal of test procedures can be developed by applying the same paradigms that are utilized in many current neuroscientific investigations that "map" the functional connectivity of brain networks. At the present time, perhaps the best methodology that can be applied clinically concerns the use of behavioral rating scales, which assess behaviors "in vivo," coupled with a few well-chosen neuropsychological measures that can track the course of cognitive development. Most importantly, however, the argument of this article proposes that a systematic evaluation of the motor system must be a fundamental part of a pediatric neuropsychological evaluation because all knowledge is initially grounded in interactive behavior, which eventually supports the development of cognition and EF, thus serving the purpose of action control.

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