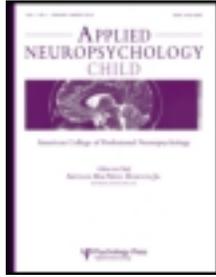


This article was downloaded by: [Leonard F. Koziol]

On: 24 February 2014, At: 09:43

Publisher: Routledge

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Applied Neuropsychology: Child

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/hapc20>

The Neuropsychology of Attention: Revisiting the "Mirsky Model"

Leonard F. Koziol ^a, Arthur W. Joyce ^b & Glen Wurglitz ^c

^a Private Practice, Arlington Heights, Illinois

^b Private Practice, Dallas, Texas

^c Private Practice, Aurora, Illinois

Published online: 24 Feb 2014.

To cite this article: Leonard F. Koziol, Arthur W. Joyce & Glen Wurglitz, Applied Neuropsychology: Child (2014): The Neuropsychology of Attention: Revisiting the "Mirsky Model", Applied Neuropsychology: Child

To link to this article: <http://dx.doi.org/10.1080/21622965.2013.870016>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

INVITED REVIEW

The Neuropsychology of Attention: Revisiting the “Mirsky Model”

Leonard F. Koziol

Private Practice, Arlington Heights, Illinois

Arthur W. Joyce

Private Practice, Dallas, Texas

Glen Wurglitz

Private Practice, Aurora, Illinois

Nearly 25 years ago, Mirsky and colleagues proposed a multiple-component model of attention. It was proposed that attention was characterized by several distinct elements that were organized into a system. A putative neuroanatomical substrate of this model of attention was proposed. This functional anatomy was primarily based upon inferences derived from brain lesion studies. Mirsky and colleagues developed a systematic clinical evaluation of this model by applying a group of neuropsychological tests. Since the introduction of what has been commonly referred to as the “Mirsky model,” significant advances have been made in our understanding of brain-behavior relationships. This article applies current neuroscientific principles to “update” our understanding of attention and the “Mirsky model.” We also demonstrate how the interpretation of neuropsychological tests can be modified according to principles of large-scale brain systems and patterns of brain network functional connectivity.

Key words: assessment of attention, brain systems and neuropsychological testing, “Mirsky model” of attention

INTRODUCTION

In a seminal paper published nearly 25 years ago, Mirsky and associates proposed a multiple-component model of attention that was unique in several ways (Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991). Attention was clinically recognized as an artificial construct that was not a unitary or global entity, but an integrated medley of more

fundamental, elemental processes identified as “focus,” “sustain,” and “shift,” functioning as a unified whole and generating the impression of a seamless cognitive attribute. Despite the fact that attention is such a critical function to everyday life, attention usually had been evaluated informally in neuropsychological protocols with practitioners making inferences about attention on the basis of preconceived notions about what a test might measure such as an incidental characteristic of a test or even only on the basis of an examiner’s impressions (Mirsky, Fantie, & Tatman, 1995). In a subsequent elaboration on the original three-component model of “focus,” “sustain,” and “shift,”

Accepted September 16, 2013.

Address correspondence to Leonard F. Koziol, 3800 N. Wilke, Suite 160, Arlington Heights, IL 60004. E-mail: lfkoziol@aol.com

Mirsky and colleagues expanded the elements of attention to include “encode,” “focus/execute,” and “stabilize” (Mirsky, 1996). The systematic assessment of these subcomponents of attention was directly related to performances on tests with well-established reliability and validity resulting in a battery of tests validated on both child and adult populations across various cultures. The same five components of attention also emerged from numerous factor-analytic studies (Kremen, Seidman, Faraone, Pepple, & Tsuang, 1992; Mirsky et al., 1991; Strauss, Thompson, Adams, Redline, & Burant, 2000). These components of attention were related to a provisional but putative neuroanatomy primarily emerging from animal and human lesion studies and likely supported by different brain regions organized into a system. In this way, Mirsky and colleagues were arguably among a small handful of the first pioneering researchers attempting to establish cognitive constructs and behaviors as manifestations of the operations of brain “systems” (Mirsky, 1987). In today’s terminology, this is perhaps equivalent to the well-recognized concept of brain “networks,” or what has also been referred to as the “functional connectivity” patterns of the brain. Cited in the literature more than 600 times (A. Mirsky, personal communication, July 3, 2013), the Mirsky model has been clinically applied to both child and adult populations with a wide variety of disorders (Duncan & Mirsky, 2004; Mirsky & Duncan, 2004), with the exact neuropsychological tests used since the Mirsky model was established. Rapid and exponential advances in the neurosciences have significantly changed our understanding of how behavior is organized within the brain, yet the Mirsky model has never been updated and the neuroanatomy driving the proposed elements of attention have never been reevaluated or revised. This article discusses the functional neuroanatomy of the Mirsky model in relation to well-documented and currently accepted neuroscientific principles. We review scientific findings and the principles of the tests proposed by Mirsky and his associates, as well as the anatomy that governs tests added or substituted by other practitioners who employ the Mirsky model. After this selective review, we conclude our discussion with a bidirectional argument that the Mirsky model of attention has informed our understanding of brain–behavior relationships and that recent findings from the neurosciences reveal the need for considerably more research for more refined modification, understanding, and conceptualization of the construct of attention.

CHARACTERISTICS OF TESTS FOR ASSESSING COMPONENTS OF ATTENTION

Mirsky and his associates asserted the most preferred, practical, and defensible methods of assessment should consist of a group of tests with several psychometric, clinical, and

cultural characteristics. Additional criteria for developing the battery included the existence of normative data for each test for different ages and educational, socioeconomic, and cultural backgrounds (Mirsky et al., 1995). The criterion of age is particularly relevant to our discussion in view of neuroscientific advances in our understanding of the development of large-scale brain networks across the lifespan. The development of a neuropsychological battery of tests included the unarguable, logical idea that each test in the battery should assess a different dissociable component of attention. The validity and reliability of each of the subtests in the proposed “battery” should be well established, as should the independent factor structure to assist in determining whether or not each test was assessing a distinct element of attention. For each task chosen for the battery, data existed for different diagnostic categories. These “categories” were diagnostic classifications defined by the *Diagnostic and Statistical Manual of Mental Disorders* (DSM) instead of identifications of specific symptoms. This is a critical point, particularly in view of the recent proposal and development of research domain criteria advocating symptomatic identification and understanding of the neurobiologic substrates of those symptoms leading to symptomatic treatment (Insel et al., 2010; Morris & Cuthbert, 2012; Sanislow et al., 2010). Reviewing how the “Mirsky model” of attention relates to the DSM categorical diagnostic system is beyond the scope of this article, and we focus upon the current neuroscientific trend toward symptomatic identification and neuroanatomic underpinnings of symptoms.

THE ENCODE ELEMENT

The “encode” component refers to the ability to initially register information. It is a mnemonic capacity that includes immediate recall as well as the capacity for holding information briefly in mind while performing some action or cognitive operation upon it (Mirsky, 1996). In this way, this component of attention overlaps with “working memory,” although it is arguable as to whether or not immediate recall and working memory are independent, dissociable functions believed to be dependent upon the hippocampus and amygdala (D’Esposito, 2008). Encoding was assessed with the Wechsler Digit Span and Arithmetic subtests, and examiners have added additional immediate-memory types of subtests, such as sentence repetition, the initial trial of a word list-learning task, and the immediate recall trial of a story recall task (Koziol & Budding, 2009).

THE SUSTAIN ELEMENT

“Sustain” was defined as the capacity to maintain attention on some aspect of the environment for an appreciable interval of time for the purpose of successful task completion. This capacity was considered the major

responsibility of rostral midbrain structures, including the mesopontine reticular formation and medial and reticular thalamic nuclei. The “sustain” element was assessed by a computerized version of the Continuous Performance Test (CPT) originally developed by Rosvold (Rosvold & Delgado, 1956) and required sustained concentration for nearly 10 min subsequently generating measures or scores of correct responses, commission errors, and reaction time. Although many CPT paradigms differ considerably and do not necessarily measure the same variables assessed by the “Mirsky model” (Riccio, Reynolds, & Lowe, 2001), a variety of CPTs are available for commercial use in clinical practice today, including variations of go–no go tasks.

THE SHIFT ELEMENT

“Shift” was operationally defined as the capacity to move from one salient aspect of the environment to another and was functionally proposed to be supported by the prefrontal cortex (PFC) including the anterior cingulate gyrus, as well as the possibility of recruitment of other unspecified brain regions. The methodology for evaluating this capacity was the Wisconsin Card-Sorting Test (WCST; Grant & Berg, 1948). The variables of interest derived from WCST performance were the number of categories achieved, the percentage of correct responses, and the number of errors. In clinical practice, many neuropsychologists describe and utilize the Trail-Making Test-Part B (TMT-B) procedure as a test of “shifting.” This practice is perhaps based upon Lezak’s description of the TMT as a measure of cognitive flexibility (Lezak, Howieson, Bigler, & Tranel, 2012). However, in numerous studies validating Mirsky’s model of attention, the TMT never loaded on the “shift” factor. Mirsky’s operational definition of the shift factor specifically reflected the abstract concept formation capacity required for attending and moving from one stimulus feature or idea to another in a flexible manner. This shift element was also recognized by Mirsky as a feature of the overarching classification of “executive functioning,” reflecting an awareness of the blurred, indistinct boundaries between “attention” and executive function (EF) and emphasizing the critical importance of the need to operationally define artificial cognitive constructs and the tests utilized to measure them (Mirsky, 1996).

THE FOCUS/EXECUTE ELEMENT

“Focus” refers to the ability to allocate attentional resources on a specific task and to simultaneously screen out distracting peripheral stimuli. The variable of interest within this dimension of attention was speed of performance for task completion. Because “focusing”

could not be differentiated from the task demand of rapid response output, the term “focus/execute” was coined to capture a more refined essence of this attentional component neuroanatomically supported by the inferior parietal lobe (IPL), the superior temporal lobe, and the striatum. The tests employed to measure the “focus/execute” element were the Wechsler Digit Symbol/Coding subtests, the TMT-Part A and TMT-B, and the Stroop Color–Word Interference Test. The Talland Cancellation Test was included in the adult battery, but not in the child version of the battery of tests because of the complex demands of that cancellation test. In neuropsychological descriptions, the focus/execute dimension is perhaps best captured by the overarching umbrella term of “processing speed.” However, as each of these tests require different cognitive demands, “processing speed” cannot be considered a single, simple, unitary cognitive construct (Reichenberg & Harvey, 2007).

STABILITY

“Stability” or reliability of attentional effort is presumably reflected in the variability of response reaction time and commission errors on CPT test performance, and it is tentatively hypothesized to be dependent upon midline-thalamic and brainstem structures.

FUNCTIONAL CONNECTIVITY, COGNITIVE NETWORKS, AND LARGE-SCALE BRAIN SYSTEMS

During the past decade, traditional ideas about the functional specialization of brain regions have dramatically changed. According to Johnson and colleagues (2005) and Friston (2002), functional specialization can be defined as the degree of information-processing specificity of an identified brain region for a particular cognitive ability or facet of cognitive operations. However, brain regions obviously do not function in isolation. The functional architecture of the brain is characterized by reciprocal connective brain profiles of the cerebro-cortical, cortical-basal ganglia, cerebro-cerebellar, and basal ganglia-cerebellar circuitry systems (Bostan, Dum, & Strick, 2010; Bostan, Dum, & Strick, 2013; Bostan & Strick, 2010; Heilman & Rothi, 2003; Koziol, Budding, & Chidekel, 2011). In addition, as we are constantly bombarded by external and internal stimuli, there must be some mechanism, or mechanisms, that solve the selection problem by dynamically activating and inhibiting different brain regions. In other words, when information is subsequently selected for further processing, there must be some way for different brain regions to communicate in order to integrate the required information. Additionally, when we “multitask,” there

must be mechanisms keeping task information in mind as we “shift” from the operations of the demands of one task to another. Clearly then, there must be processes allowing various brain regions to interact and coordinate adaptive activities as we constantly engage the changing world during the course of the day. The “functional integration” of distal brain regions refers to transient, dynamically changing, contextually specific interactions that convey information through subsets of anatomical connections among a limited number of brain regions engaged by a particular cognitive process (Koziol & Stevens, 2012). These connections are supported by the “superhighways” of the white matter tracts supporting communications between both distal and proximal brain regions (Catani et al., 2012; Schmahmann, Smith, Eichler, & Filley, 2008).

These changing patterns of functional connectivity required for adaptation appear to be reflected within the operations of seven large-scale brain systems (Yeo et al., 2011). The *frontoparietal network* (FPN) consists of the dorsolateral PFC (DLPFC), the anterior cingulate cortex

(ACC), the anterior PFC, the lateral cerebellum, the anterior insula, the caudate nucleus, and the IPL. This “cognitive control” network, which includes working-memory functions, is typically engaged when information or rules need to be kept in mind to guide behavior during effortful cognitive task performance.

The *ventral attention network* includes the temporoparietal junction, the supramarginal gyrus, the frontal operculum, and the anterior insula. This network provides salience information and allows for the identification of “objects” and “what” these objects are used for.

The *dorsal attention network*, anchored in the intraparietal sulcus and frontal eye fields, participates in goal-directed executive control processes by managing spatial attention and attentional shifting, in conjunction with identifying where “objects” are and knowing “how” to use them. The interaction of the ventral and dorsal networks guides purposeful behavior as we constantly interact with our dynamically changing environment.

The occipital lobe, the lateral temporal region, and the superior parietal lobule make up the *visual network* and interact with the ventral and dorsal networks in sustaining attention, suppressing attention to irrelevant stimuli, and closely interacting with these “action control” regions. The *limbic network* interacts with these systems to generate motivational and reward influences.

The *sensory motor network* includes the supplementary motor cortex, the primary motor cortex, the ventral premotor cortex, the primary and secondary sensory cortices, and certain subcortical structures such as the putamen, the thalamus, and the cerebellum.

Finally, the *default mode network* (DMN) is anchored in the anterior medial PFC and the posterior cingulate cortex, as well as two other regions, including the dorso-medial prefrontal system and the medial temporal-lobe memory system. There is notable and significant activity within the DMN until immediate goal-directed cognitive processing is required. These brain systems are illustrated in Figure 1.

It has been established that these brain networks demonstrate remarkable consistency across subjects, with children and young adults exhibiting very similar patterns of network organization (Supekar, Musen, & Menon, 2009). In fact, these brain systems can even be studied in infants and very young children (Uddin, Supekar, & Menon, 2010).

One primary difference concerns a weakening of proximal connections and a strengthening of distal connections during the course of development. There is a pruning of local connections and a strengthening of long-range connectivity with age accompanied by a shift from diffuse to focal activation patterns. As children develop, even though they demonstrate the same large-scale brain systems, the magnitude of activation in key specific frontal regions increases along with a concomitant decrease of

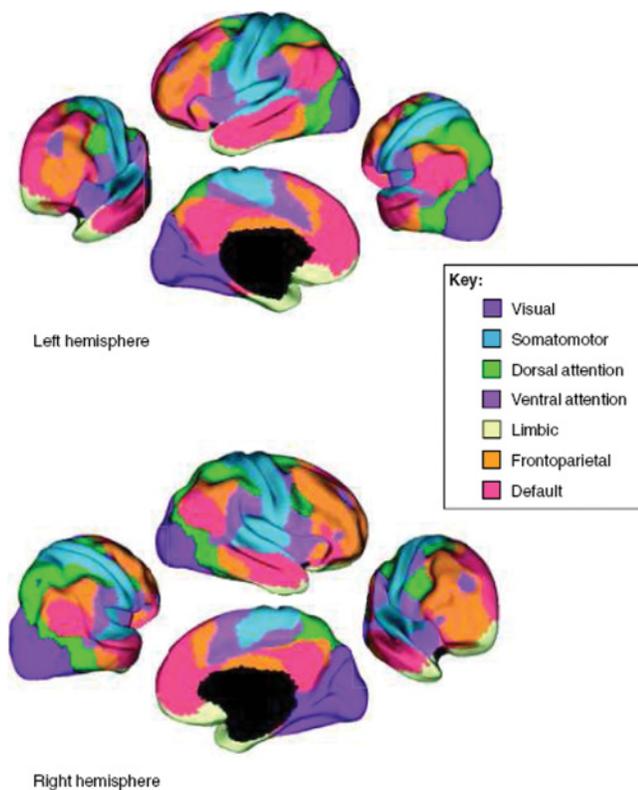


FIGURE 1 Seven-network parcellation ($N=1,000$). Coarse (seven-network) parcellation of the human cerebral cortex obtained through clustering of resting-state fMRI data of 1,000 subjects. At this resolution, the association cortex is distinguished from the primary sensorimotor cortex. The association networks converged on and extended networks previously described in the resting-state literature, including the dorsal attention, ventral attention, frontoparietal control, and default networks. *Source:* Castellanos & Proal (2012). (Color figure available online.)

© 2012 Elsevier. Reproduced by permission of Elsevier. Permission to reuse must be obtained from the rightsholder.

activation in more widespread nonspecific brain regions (Durstun et al., 2006). These developmental changes presumably reflect an increase in cognitive control resources. It has also been demonstrated that the cerebellum links to these brain systems in a highly differentiated and segregated manner (Buckner, Krienen, Castellanos, Diaz, & Yeo, 2011). For the Mirsky model to remain viable across the lifespan, it must account for these developmental changes so theory is directly applied to clinical practice.

MIRSKY'S ELEMENTS OF ATTENTION AND LARGE-SCALE BRAIN SYSTEMS

The functional neuroanatomy of the components of attention proposed by Mirsky and colleagues was considered provisional and tentative, based upon inferences from animal and human lesion studies that made logical, justifiable “common sense” as it applied to neuroscientific findings available at the time. Within the context of today’s neuroscientific technologies, some of the tests used in the Mirsky model have been successfully applied as “probes” in functional neuroimaging paradigms further developing and refining our understanding of brain–behavior relationships. Therefore, it is now possible to examine the elements of attention identified by Mirsky and colleagues within the context of the functionally identified large-scale brain networks.

THE ENCODE ELEMENT REVISITED

Although it was initially proposed that the “encode” element was mediated by the hippocampus and amygdala, Digit Span and Arithmetic subtest performances are not supported by these brain regions. Squire (1987) and Squire and Shimamura (1986) have demonstrated that even severely amnesic patients can have a normal digit span. Similarly, the amygdala is not a component of this memory system as reported by these investigators. H.M., undoubtedly the most widely known case of a person with amnesia, had a normal digit span of 6. Shrager, Levy, Hopkins, and Squire (2008) have demonstrated that “working memory” and hippocampal memory systems are clearly dissociable and are dependent upon the operations of systems that can interact.

In a positron emission tomography (PET) scan investigation of normal control participants, Digits Forward and Digits Backward (DB; Wechsler, 1997) performance recruited an overlapping functional system consistent with the FPN associated with working memory (Gerton et al., 2004). This network included the right DLPFC, the bilateral IPL, as well as the ACC; DB additionally

recruited the 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 functional magnetic resonance imaging (fMRI; Dengtang, Yifeng, & Zheng, 2004). Cerebellar regions were also activated, a finding that should not be unexpected, because activation of the cerebellum is evident on nearly all working-memory tasks, including verbal working-memory tasks, and interacts with numerous brain regions across tasks as part of a “network” (Ivry & Justus, 2001; Marvel & Desmond, 2010; Ravizza et al., 2006).

The medial occipital cortex, including higher-level and lower-level visual-processing areas, was robustly activated and this could not be simply attributed to “visual processing.” As the “visual network” supports and interacts with the dorsal and ventral attention networks, auditory processing has been demonstrated to follow the organizational profiles of these same dorsal and ventral systems, and the 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 supporting implicit auditory–visual interactions outside of conscious awareness, while simultaneously supporting working memory (Arnott & Alain, 2011; Banich & Compton, 2011; Naatanen, Kujala, & Winkler, 2011; Salmi, Rinne, Degerman, & Alho, 2007). A study by Li and colleagues recently linked the working memory involved in the DB task to the superior temporal gyrus, interacting with the ACC and frontoinsula cortex within the “salience” network, which is part of the motivational system (Li, Qin, Zhang, Jiang, & Yu, 2012).

It is widely assumed the FPN is similarly activated in children. However, although 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 with adolescents, children activate more ventromedial regions including the caudate and insula, while adolescents activate more diffuse regions of frontal and parietal cortices. Therefore, between childhood and adolescence, there is a more consistent activation of the FPN, followed by a refinement of these network regions between adolescence and adulthood (Tau & Peterson, 2010).

Meyers and Rohling (2009) 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 event related potentials (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 participant (Simon & Rivera, 2007). Although most studies have been conducted with adults, there is evidence to support the conclusion that similar network activity is recruited in typically developing children as early as third grade. Brain regions involved in effort, such as the ACC, and the working-memory network are more strongly activated in these children, with increasingly less activation as arithmetic operations become increasingly automated (Kucian, von Aster, Loenneker, Dietrich, & Martin, 2008). However, children with neurodevelopmental disorders demonstrate different patterns of activation, and because there are so few child studies, caution is warranted in generalizing conclusions (Piazza et al., 2010). In a recent fMRI study that compared 7- to 12-year-old typically developing children and children with autism spectrum disorder (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 (Luculano et al., 2014). Additionally, there is clear evidence that cerebellar integrity may be a primary contributor to the acquisition of procedural arithmetic knowledge in children (Lonnemann, Linkersdorfer, Heselhaus, Hasselhorn, & Linberg, 2011).

The Wechsler Arithmetic subtests clearly consist of items requiring multiple component processes. Because these subtests have never been systematically studied with respect to age or on children with neurodevelopmental disorders, it would appear very unlikely that a reliable “network” unique to these subtests would be identified because of developmental age differences and obvious and subtle changes in test item composition. As Ansari (2010) observes, “It is not simply the case that brain regions are recruited by children to a lesser degree, than they are by adults, but instead that the network of activated regions differs between children and adults” (p. 126).

Perhaps the best that can be said is that within the Mirsky model of attention, the Arithmetic subtest assesses aspects of working memory, while a single, unique neuro-anatomic underpinning cannot be identified for “arithmetic.” Rottschy and colleagues (2012) confirmed a bilateral frontoparietal core or hub working-memory network associated with the changing functional connectivity patterns that are necessarily task demand-dependent.

In practice, clinicians sometimes include immediate recall subtests such as the initial trial of a word list-learning task. Although the demand of immediate word list recall seems similar to digit span recall, this similarity is not observed from a neuroanatomic perspective. For example, an fMRI investigation revealed that on Trial 1 of the California Verbal Learning Test, 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 participants with better overall memory ability (Sterling et al., 2001). Therefore, even within a “verbal” domain, immediate recall is not a unitary entity recruiting a well-defined brain region. These findings seem particularly relevant for children, who are obviously in the process of acquiring a vocabulary. This can contribute to variability in performances on different subtests within the encoding dimension of the “Mirsky model,” therefore affecting applied clinical test interpretation inferences that might have nothing to do with “attention.” Therefore, when adding subtests to this model, considerable caution is required of test interpretation to avoid misleading diagnostic conclusions.

Although these findings illustrate that subtle differences in tasks recruit different functional anatomical connectivity profiles, reviewing other tasks such as sentence repetition and narrative recall are beyond the scope of this selective review. Including them, however, would only further reinforce verbal tasks can recruit both the left-hemisphere and right-hemisphere brain networks; the left hemisphere–verbal and right hemisphere–nonverbal dichotomy of specialization is very artificial and potentially misleading (Spree, 2011), and the data support the view that the brain is organized along a novelty versus routinization principle (Goldberg & Costa, 1981; MacNeilage, Rogers, & Vallortigara, 2009).

In general, the “encode” element of attention appears to be supported by the FPN. It is currently believed that the FPN operates as a “flexible hub” (Cole et al., 2013). 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. In addition, the patterns of activation that were recruited were consistent across practiced or familiar as well as novel tasks. In this regard, the reuse of these dynamically changing functional connectivity patterns becomes very efficient and conserves precious cognitive resources. These patterns of flexible connectivity facilitate novel, adaptive task performance. The FPN

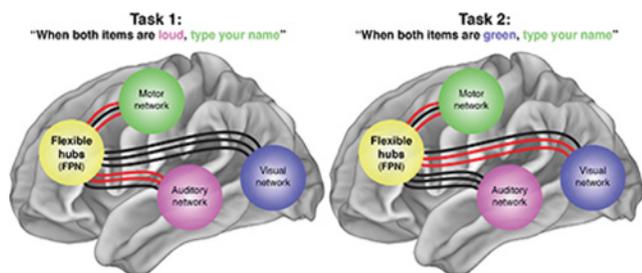


FIGURE 2. The brain's FPN region is shown to play a central role in routing the processing of cognitive tasks among a range of specialized cognitive processing networks, such as the linkages shown here among the visual, auditory, and motor networks. *Source:* Cole et al. (2013). (Color figure available online.)

© 2013 Nature Publishing Group. Reproduced by permission of Nature Publishing Group. Permission to reuse must be obtained from the rightsholder.

functions in a critical role for “cognitive control” and for the adaptive implementation of task demands as situations develop or unfold. These findings therefore raise critical questions that are well beyond the scope of this article. For example, it has been traditional to evaluate the FPN as a “static” aspect of cognition. However, the FPN “hub” interacts with cognitive and motor networks, raising questions about the clinical need for evaluating procedural learning systems, which are of critical importance for functioning within a changing environment. The flexibility of the FPN is illustrated in Figure 2.

REVISITING THE SUSTAIN AND STABILITY ELEMENTS

Neuroimaging techniques including single-photon emission computed tomography, PET, and fMRI identify a distributed, large-scale brain network supporting performance on the CPT (Criaud & Boulinguez, 2013; Häger et al., 1998). This network is primarily lateralized to the right hemisphere, although studies with different CPT and inhibition paradigms have been reported to recruit left-hemisphere networks. The DLPFC and ventral medial frontal cortex are activated along with subcortical regions of the basal ganglia, including the striatum, globus pallidus, and thalamus, which project back to the cortex. Correct stimulus identification, or vigilance, appears to be mediated by prefrontal–parietal connections (Posner & Petersen, 1990). Errors of commission appear to be governed by the ventral, inferior fronto-cortico-striatal-pallidal-thalamo-cortical loop, consistent with the direct and indirect pathways of the corticostriatal system (Schulz et al., 2004; Stevens, Kiehl, Pearlson, & Calhoun, 2007; Stevens, Pearlson, & Kiehl, 2007). Errors of commission/disinhibition and reaction times reflect attentional stability concomitant with age. These studies also report correct

identifications increase with age; errors of commission decrease with age; and reaction times decrease from childhood through adolescence, following a developmental trajectory. Correct identifications/errors of omission and errors of commission *never* follow the normal distribution of a “bell-shaped” curve at any age as reported by Mirsky (A. Mirsky, personal communication, March 5, 2008). Therefore, statistical procedures that “force” variables of interest into “standard scores” do no justice to the findings.

Response inhibition, as measured by correct identifications and a relative absence of errors of commission, does not rely upon a single frontostriatal network. Instead, three independent networks form an interdependent, hierarchically organized system. A comprehensive review of these neural network dynamics is beyond the scope of this article. With successful inhibition, activity within premotor regions is reduced, brain regions that translate sensory information into certain actions demonstrate decreased activity, and cognitive control systems, such as the FPN, are activated presumably for the purpose of accomplishing goal-directed EF behaviors. Therefore, it is important to understand that successful performance within this “element” of attention can generate adaptive behaviors going well beyond the initial implications of the “Mirsky model.” Considerable caution should be exercised in applying these findings to clinical evaluations as numerous commercially available and experimental versions of CPT and inhibition paradigms are organized along different parameters. Even subtle changes in task demands recruit different brain systems (Mostofsky, Newschaffer, & Denckla, 2003; Riccio, Reynolds, Lowe, & Moore, 2002). There is a dynamic interaction between vigilant attention and inhibitory abilities, which are easily influenced by frequency, novelty, and rate of stimulus presentations (Robertson, 2004) and clearly limit the practitioner’s ability to generalize these findings.

THE SHIFT ELEMENT REVISITED

Mirsky’s tentative anatomy of the WCST was based upon cortical brain regions, but he left open the possibility of other brain system involvement. An event-related fMRI study revealed distinct neural networks are recruited during the performance of different stages of the task, going well beyond the DLPFC and ACC (Monchi, Petrides, Petre, Worsley, & Dagher, 2001). The WCST is one type of rule-based categorization test requiring the identification of categories discoverable by an explicit reasoning process (Ashby & Ennis, 2006). During the performance of this task, activity within the DLPFC increases when subjects receive “feedback” about being “right or wrong” that is then related to the earlier events, or trials, retained in working memory. This activation likely reflects a general role of the PFC in monitoring the

events in working memory. However, with “wrong” responses, the negative “feedback” signals the need for a mental “shift” to responding in a different way thereby activating a specific cortical-basal ganglia “loop” consisting of the ventral PFC, the caudate nucleus, and the dorsomedial thalamus. The activation of the caudate actually precedes PFC activation, alerting the PFC to a change and thus revealing the sensitivity of the caudate to changes in context. The caudate is believed to be critically important for recognizing behavioral context and actually modulating activity within the cortex (Seger & Cincotta, 2006). In this case, the caudate “signals” the PFC to think. The most posterior regions of the PFC are active throughout task performance, likely indicative of its role in associative learning, or linking specific actions to stimuli. Activity within the putamen increased only when matching a card right after negative “feedback,” but not after correct responses. This might imply greater involvement of the putamen under conditions of novelty instead of during the performance of routine cognitive activities, specifically seen in “correct” responses. The ACC was also activated bilaterally with negative feedback, consistent with its role in “monitoring” how well things are going (Cockburn & Frank, 2011). The posterior parietal lobes were active throughout the task, consistent with its role in category learning. The parietal lobes project to the body/tail of the caudate, and these are the only regions exhibiting increased activity for quick rule learners as opposed to those who learn categorization rules slowly (Cincotta & Seger, 2007; Seger, 2006, 2008). Shifts in thinking and reasoning processes then, as measured by rule learning, reveal a dynamically changing recruitment of brain systems, therefore activating and integrating aspects of the frontoparietal, dorsal, ventral, and limbic large-scale brain networks. Therefore, it is clear the WCST can no longer be considered a “frontal-lobe” test. Similarly, how WCST performance recruits patterns of functional connectivity in typically developing children has not been studied.

THE FOCUS/EXECUTE ELEMENT REVISITED

The Digit Symbol/Coding subtests and the Talland Cancellation Task (not commercially available) have apparently not been systematically investigated through neuroimaging technologies because of the practical limitations associated with applying these technologies to these tasks. Neuroimaging investigations have not focused on the focus/execute component in children. While some clinicians have included the Wechsler Symbol Search (SS) subtest within the focus/execute component, a modified version of this subtest has been studied with fMRI. SS performance recruited the bilateral medial occipital,

occipitoparietal, occipitotemporal, and parietal cortices and the DLPFC. Slower processing speed was associated with greater activity in these areas and was especially noted in the left DLPFC (Sweet et al., 2005). Therefore, SS recruited widely distributed large-scale brain networks, including the visual, ventral, and dorsal attention networks, as well as the frontoparietal network necessary for cognitive control. Although slower speed of performance was associated with greater activation, we interpret this finding as revealing that slower-performing participants had to concentrate, think, and “work” harder in completing this task.

Focus/execute emphasizes a speed-of-performance factor. In the Mirsky model, speed of performance was the variable of interest in the TMT-B. However, TMT-B performance is sensitive to the “shifting” of cognitive set and correlates moderately with perseverative errors on the WCST (Kortte, Horner, & Windham, 2002). Perseverative errors were not a variable of interest within the Mirsky model, which might explain why TMT-B did not load on a “shift” factor.

The TMT-B would be predicted to recruit a variety of brain systems as the requirement of mentally tracking numbers and letters places a heavy demand on working memory, theoretically activating the FPN. The search for numbers and letters predicts interactions between the ventral (object identification) and dorsal (control of the frontal eye fields) networks, as well as the visual attention network supporting both of these systems, while the motor aspect should recruit aspects of the sensory motor network. Therefore, although this is clearly a multiple-component subtest, it is not at all surprising that a variation of the original TMT-B found in the Delis-Kaplan Executive Function System version recruited multiple, widespread brain regions consistent with what would be predicted on the basis of our understanding of functional connectivity and large-scale brain systems (Pa et al., 2010). Similarly, inherent in the functional connectivity necessary for successful task completion, it should be no surprise that speed of performance on the TMT-B is highly dependent upon the integrity of white-matter tracts (Perry et al., 2009).

The Stroop Color–Word Interference task appears to be highly dependent upon the frontoparietal cognitive control network. While the visual, ventral, and dorsal attention networks are obviously implicated in identifying the colors, the words, and in the frontal eye field control necessary to meet the basic task demands, the DLPFC and ACC appear to be recruited in different ways during different phases of task performance. If there is no conflict between the stimulus and response, as in word reading and color naming, then posterior regions of the ACC are differentially activated (Milham et al., 2001). Posterior regions of the DLPFC send “top–down” signals to the regions of the posterior sensory cortex

needed to process task-relevant information and activate the appropriate attentional set, as in the difference between naming colors and reading words. Anterior regions of the DLPFC bias processing toward task demand attributes, as is required for naming the color rather than the color being named by the word during the interference trial. Posterior regions of the ACC participate in this biasing for the actual selection of the appropriate response. However, the most anterior regions of the ACC participate in response monitoring and in evaluating the appropriateness of the response (Banich & Compton, 2011). Therefore, the Stroop requires a dynamically changing pattern of functional connectivity such that not only are multiple networks recruited for different phases of the task, but there is actually a hierarchically organized level of control within the frontoparietal system. Although Stroop task performance has not been systematically studied within the pediatric population, this brain network refinement develops from adolescence to young adulthood with typically developing children likely recruiting more diffuse patterns of brain activation.

SUMMARY AND CONCLUSIONS

It is critically important to directly apply theory to practice in neuropsychological evaluation. The “Mirsky model” remains relevant today as it did 25 years ago when it replaced the diffuse and global concept of attention by identifying several distinct processes and applied these components to systematic clinical assessment. Although other models of attention exist, as do commercially available test batteries that purport to measure attention, Mirsky and colleagues utilized commonly available neuropsychological tests linking elemental processes of attention to a putative system of brain structures. This makes the Mirsky model unique from commercially available test batteries that have not all been linked to neuroanatomic structure and function. We have revisited the Mirsky model and demonstrated how the proposed elements of attention should be conceptualized within the context of currently emerging neuroscientific principles of brain–behavior relationships, identified through the study of large-scale brain networks. This is admittedly a selective review representing a “sample” of how the field might “merge” with rapidly developing neuroscientific endeavors and supports the conclusion that perhaps there is no such thing as “attention,” but instead, there are several “attentions” (Posner & Boies, 1971).

Studies of adult normal control participants predominate over studies of typically developing children. However, we have reviewed the fundamental principles of the development of these large-scale brain systems to continue to make the Mirsky model applicable to both

pediatric and adult neuropsychological evaluation. This discussion, therefore, represents an “interim solution” and a foundation for more research, particularly within the child population, to understand the trajectory of the development of the components of attention. In presenting a foundation for practical, applied test interpretation and for further development of hypotheses for ongoing research in union with emerging neuroscientific findings, the field of neuropsychology can fundamentally reorganize and standardize the manner by which attention is conceptualized, understood, and evaluated for functionally useful evaluation.

REFERENCES

- Ansari, D. (2010). Neurocognitive approaches to developmental disorders of numerical and mathematical cognition: The perils of neglecting the role of development. *Learning and Individual Differences, 20*, 123–129.
- Arnott, S. R., & Alain, C. (2011). The auditory dorsal pathway: Orienting vision. *Neuroscience & Biobehavioral Reviews, 35*, 2162–2173.
- Ashby, F. G., & Ennis, J. M. (2006). The role of the basal ganglia in category learning. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 46, pp. 1–36). New York, NY: Elsevier.
- Banich, M. T., & Compton, R. J. (2011). *Cognitive neuroscience* (3rd ed.). Belmont, CA: Wadsworth, Cengage Learning.
- Bostan, A. C., Dum, R. P., & Strick, P. L. (2010). The basal ganglia communicate with the cerebellum. *Proceedings of the National Academy of Sciences, 107*, 8452–8456.
- Bostan, A. C., Dum, R. P., & Strick, P. L. (2013). Cerebellar networks with the cerebral cortex and basal ganglia. *Trends in Cognitive Sciences, 17*, 241–254.
- Bostan, A. C., & Strick, P. L. (2010). The cerebellum and basal ganglia are interconnected. *Neuropsychology Review, 20*, 261–270.
- Buckner, R. L., Krienen, F. M., Castellanos, A., Diaz, J. C., & Yeo, B. T. (2011). The organization of the human cerebellum estimated by intrinsic functional connectivity. *Journal of Neurophysiology, 106*, 2322–2345.
- Castellanos, F. X., & Proal, E. (2012). Large-scale brain systems in ADHD: Beyond the prefrontal-striatal model. *Trends in Cognitive Science, 16*(1), 17–26.
- Catani, M., Dell’acqua, F., Bizzi, A., Forkel, S. J., Williams, S. C., Simmons, A., ... Thiebaut de Schotten, M. (2012). Beyond cortical localization in clinico-anatomical correlation. *Cortex, 48*, 1262–1287.
- Cincotta, C. M., & Seger, C. A. (2007). Dissociation between striatal regions while learning to categorize via feedback and via observation. *Journal of Cognitive Neuroscience, 19*, 249–265.
- Cockburn, J., & Frank, M. J. (2011). Reinforcement learning, conflict monitoring, and cognitive control: An integrative model of cingulate-striatal interactions and the ERN. In R. B. Mars, J. Sallet, M. F. S. Rushworth, & N. Yeung (Eds.), *Neural basis of motivational and cognitive control* (pp. 311–331). Cambridge, MA: MIT Press.
- Cole, M. W., Reynolds, J. R., Power, J. D., Repovs, G., Anticevic, A., & Braver, T. S. (2013). Multi-task connectivity reveals flexible hubs for adaptive task control. *Nature Neuroscience, 16*(9), 1348–1355.
- Criaud, M., & Boulinguez, P. (2013). Have we been asking the right questions when assessing response inhibition in go/no-go tasks with fMRI? A meta-analysis and critical review. *Neuroscience & Biobehavioral Reviews, 37*, 11–23.
- Dengtang, L., Yifeng, X., & Zheng, L. (2004). Functional magnetic resonance imaging of backward digit span task in first-episode

- schizophrenia patients before and after treatment. *Shanghai Archives of Psychiatry*, 16(5), 66–81.
- D'Esposito, M. (2008). Working memory. *Handbook of Clinical Neurology*, 88, 237–247.
- Duncan, C. C., & Mirsky, A. F. (2004). The attention battery for adults: A systematic approach to assessment. In G. Goldstein, S. R. Beers, & M. Hersen (Eds.), *Comprehensive handbook of psychological assessment* (pp. 277–292). Hoboken, NJ: John Wiley & Sons.
- Durston, S., Davidson, M. C., Tottenham, N., Galvan, A., Spicer, J., Fossella, J. A., & Casey, B. J. (2006). A shift from diffuse to focal cortical activity with development. *Developmental Science*, 9, 1–8.
- Friston, K. (2002). Functional integration and inference in the brain. *Progress in Neurobiology*, 68, 113–143.
- Gerton, B. K., Brown, T. T., Meyer-Lindenberg, A., Kohn, P., Holt, J. L., Olsen, R. K., & Berman, K. F. (2004). Shared and distinct neurophysiological components of the digits forward and backward tasks as revealed by functional neuroimaging. *Neuropsychologia*, 42, 1781–1787.
- Goldberg, E., & Costa, L. D. (1981). Hemisphere differences in the acquisition and use of descriptive systems. *Brain and Language*, 14, 144–173.
- Grant, D. A., & Berg, E. A. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-problem. *Journal of Experimental Psychology*, 38, 404–411.
- Häger, F., Volz, H. P., Gaser, C., Mentzel, H. J., Kaiser, W. A., & Sauer, H. (1998). Challenging the anterior attentional system with a continuous performance task: A functional magnetic resonance imaging approach. *European Archives of Psychiatry and Clinical Neuroscience*, 248, 161–170.
- Heilman, K. M., & Rothi, L. G. (2003). Apraxia. In K. M. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology* (4th ed., pp. 215–235). New York, NY: Oxford University Press.
- Insel, T., Cuthbert, B., Garvey, M., Heinssen, R., Pine, D. S., Quinn, K., ... Wang, P. (2010). Research domain criteria (RDoC): Toward a new classification framework for research on mental disorders. *American Journal of Psychiatry*, 167, 748–751.
- Ivry, R. B., & Justus, T. C. (2001). A neural instantiation of the motor theory of speech perception. *Trends in Neurosciences*, 24, 513–515.
- Johnson, M. H., Griffin, R., Csibra, G., Halit, H., Farroni, T., de Haan, M., ... Richards, J. (2005). The emergence of the social brain network: Evidence from typical and atypical development. *Development and Psychopathology*, 17, 599–619.
- Kortte, K. B., Horner, M. D., & Windham, W. K. (2002). The Trail Making Test, Part B: Cognitive flexibility or ability to maintain set? *Applied Neuropsychology*, 9, 106–109.
- Koziol, L. F., & Budding, D. E. (2009). *Subcortical structures and cognition: Implications for neuropsychological assessment*. New York, NY: Springer.
- Koziol, L. F., Budding, D. E., & Chidekel, D. (2011). Sensory integration, sensory processing, and sensory modulation disorders: Putative functional neuroanatomic underpinnings. *Cerebellum*, 10, 770–792.
- Koziol, L. F., & Stevens, M. C. (2012). Neuropsychological assessment and the paradox of ADHD. *Applied Neuropsychology: Child*, 1, 79–89.
- Kremen, W. S., Seidman, L. J., Faraone, S. V., Pepple, J. R., & Tsuang, M. T. (1992). Attention/information-processing factors in psychotic disorders. Replication and extension of recent neuropsychological findings. *Journal of Nervous and Mental Disease*, 180, 89–93.
- Kucian, K., von Aster, M., Loenneker, T., Dietrich, T., & Martin, E. (2008). Development of neural networks for exact and approximate calculation: A fMRI study. *Developmental Neuropsychology*, 33, 447–473.
- Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). *Neuropsychological assessment* (5th ed.). Oxford, UK: Oxford University Press.
- Li, R., Qin, W., Zhang, Y., Jiang, T., & Yu, C. (2012). The neuronal correlates of digits backward are revealed by voxel-based morphometry and resting-state functional connectivity analyses. *PLoS One*, 7(2), e31877.
- Lonnemann, J., Linkersdorfer, J., Heselhaus, V., Hasselhorn, M., & Linberg, S. (2011). Relations between balancing and arithmetic skills in children—evidence of cerebellar involvement? *Journal of Neurolinguistics*, 24, 592–601.
- Luculano, T., Rosenberg-Lee, M., Supekar, K., Lynch, C. J., Khouzam, A., Phillips, J., ... Menon, V. (2014). Brain organization underlying superior mathematical abilities in children with autism. *Biological Psychiatry*, 75(3), 223–230.
- MacNeilage, P. F., Rogers, L. J., & Vallortigara, G. (2009). Origins of the left & right brain. *Scientific American*, 301(1), 60–67.
- Marvel, C. L., & Desmond, J. E. (2010). Functional topography of the cerebellum in verbal working memory. *Neuropsychology Review*, 20, 271–279.
- Meyers, J. E., & Rohling, M. L. (2009). CT and MRI correlations with neuropsychological tests. *Applied Neuropsychology*, 16, 237–253.
- Milham, M. P., Banich, M. T., Webb, A., Barad, V., Cohen, N. J., Wszalek, T., & Kramer, A. F. (2001). The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. *Brain Research: Cognitive Brain Research*, 12, 467–473.
- Mirsky, A. F. (1987). Behavioral and psychophysiological markers of disordered attention. *Environmental Health Perspectives*, 74, 191–199.
- Mirsky, A. F. (1996). Disorders of attention: A neuropsychological perspective. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 71–95). Baltimore, MD: Paul H. Brookes.
- Mirsky, A. F., Anthony, B. J., Duncan, C. C., Ahearn, M. B., & Kellam, S. G. (1991). Analysis of the elements of attention: A neuropsychological approach. *Neuropsychology Review*, 2, 109–145.
- Mirsky, A. F., & Duncan, C. C. (2004). The attention battery for children: A systematic approach to assessment. In G. Goldstein, S. R. Beers, & M. Hersen (Eds.), *Comprehensive handbook of psychological assessment* (pp. 277–292). Hoboken, NJ: John Wiley & Sons.
- Mirsky, A. F., Fantie, B., & Tatman, J. (1995). Assessment of attention across the lifespan. In R. L. Mapou & J. Spector (Eds.), *Neuropsychological assessment: A clinical approach* (pp. 17–48). New York, NY: Plenum.
- Monchi, O., Petrides, M., Petre, V., Worsley, K., & Dagher, A. (2001). Wisconsin Card Sorting revisited: Distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging. *Journal of Neuroscience*, 21, 7733–7741.
- Morris, S. E., & Cuthbert, B. N. (2012). Research domain criteria: Cognitive systems, neural circuits, and dimensions of behavior. *Dialogues in Clinical Neuroscience*, 14, 29–37.
- Mostofsky, S. H., Newschaffer, C. J., & Denckla, M. B. (2003). Overflow movements predict impaired response inhibition in children with ADHD. *Perceptual and Motor Skills*, 97, 1315–1331.
- Naatanen, R., Kujala, T., & Winkler, I. (2011). Auditory processing that leads to conscious perception: A unique window to central auditory processing opened by the mismatch negativity and related responses. *Psychophysiology*, 48, 4–22.
- Pa, J., Possin, K. L., Wilson, S. M., Quitania, L. C., Kramer, J. H., Boxer, A. L., ... Johnson, J. K. (2010). Gray matter correlates of set-shifting among neurodegenerative disease, mild cognitive impairment, and healthy older adults. *Journal of the International Neuropsychological Society*, 16, 640–650.
- Perry, M. E., McDonald, C. R., Hagler, D. J., Jr., Gharapetian, L., Kuperman, J. M., Koyama, A. K., ... McEvoy, L. K. (2009). White matter tracts associated with set-shifting in healthy aging. *Neuropsychologia*, 47, 2835–2842.
- Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., ... Zorzi, M. (2010). Developmental trajectory of

- number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, 116, 33–41.
- Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review*, 78(5), 391–408.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25–42.
- Ravizza, S. M., McCormick, C. A., Schlerf, J. E., Justus, T., Ivry, R. B., & Fiez, J. A. (2006). Cerebellar damage produces selective deficits in verbal working memory. *Brain*, 129, 306–320.
- Reichenberg, A., & Harvey, P. D. (2007). Neuropsychological impairments in schizophrenia: Integration of performance-based and brain imaging findings. *Psychological Bulletin*, 133, 833–858.
- Riccio, C. A., Reynolds, C. R., & Lowe, P. A. (2001). *Clinical applications of continuous performance tests: Measuring attention and impulsive responding in children and adults*. New York, NY: John Wiley.
- Riccio, C. A., Reynolds, C. R., Lowe, P. A., & Moore, J. J. (2002). The continuous performance test: A window on the neural substrates for attention? *Archives of Clinical Neuropsychology*, 17, 235–272.
- Robertson, I. H. (2004). Examining attentional rehabilitation. In M. I. Posner (Ed.), *Cognitive neuroscience of attention* (pp. 407–419). New York, NY: Guilford.
- Rosvold, H. E., & Delgado, J. M. (1956). The effect on delayed-alternation test performance of stimulating or destroying electrically structures within the frontal lobes of the monkey's brain. *Journal of Comparative and Physiological Psychology*, 49, 365–372.
- Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., ... Eickhoff, S. B. (2012). Modelling neural correlates of working memory: A coordinate-based meta-analysis. *NeuroImage*, 60, 830–846.
- Salmi, J., Rinne, T., Degerman, A., & Alho, K. (2007). Orienting and maintenance of spatial attention in audition and vision: An event-related brain potential study. *The European Journal of Neuroscience*, 25, 3725–3733.
- Sanislow, C. A., Pine, D. S., Quinn, K. J., Kozak, M. J., Garvey, M. A., Heinssen, R. K., ... Cuthbert, B. N. (2010). Developing constructs for psychopathology research: Research domain criteria. *Journal of Abnormal Psychology*, 119, 631–639.
- Schmahmann, J. D., Smith, E. E., Eichler, F. S., & Filley, C. M. (2008). Cerebral white matter: Neuroanatomy, clinical neurology, and neurobehavioral correlates. *Annals of the New York Academy of Sciences*, 1142, 266–309.
- Schulz, K. P., Fan, J., Tang, C. Y., Newcorn, J. H., Buchsbaum, M. S., Cheung, A. M., & Halperin, J. M. (2004). Response inhibition in adolescents diagnosed with attention deficit hyperactivity disorder during childhood: An event-related fMRI study. *American Journal of Psychiatry*, 161, 1650–1657.
- Seger, C. A. (2006). The basal ganglia in human learning. *Neuroscientist*, 12, 285–290.
- Seger, C. A. (2008). How do the basal ganglia contribute to categorization? Their roles in generalization, response selection, and learning via feedback. *Neuroscience & Biobehavioral Reviews*, 32, 265–278.
- Seger, C. A., & Cincotta, C. M. (2006). Dynamics of frontal, striatal, and hippocampal systems during rule learning. *Cerebral Cortex*, 16, 1546–1555.
- Shrager, Y., Levy, D. A., Hopkins, R. O., & Squire, L. R. (2008). Working memory and the organization of brain systems. *Journal of Neuroscience*, 28, 4818–4822.
- Simon, T. J., & Rivera, S. M. (2007). Neuroanatomical approaches to the study of mathematical ability and disability. In D. B. Berch & M. L. M. M. Mazzocco (Eds.), *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities* (pp. 283–305). Baltimore, MD: Paul H. Brookes.
- Spren, O. (2011). Nonverbal learning disabilities: A critical review. *Child Neuropsychology*, 17, 418–443.
- Squire, L. R. (1987). The organization and neural substrates of human memory. *International Journal of Neurology*, 21(22), 218–222.
- Squire, L. R., & Shimamura, A. P. (1986). Characterizing amnesic patients for neurobehavioral study. *Behavioral Neuroscience*, 100, 866–877.
- Sterling, C., Johnson, S. C., Saykin, A. J., Flashman, L. A., McAllister, T. W., & Sparling, M. B. (2001). Brain activation on fMRI and verbal memory ability: Functional neuroanatomic correlates of CVLT performance. *Journal of the International Neuropsychological Society*, 7, 55–62.
- Stevens, M. C., Kiehl, K. A., Pearson, G. D., & Calhoun, V. D. (2007). Functional neural networks underlying response inhibition in adolescents and adults. *Behavioural Brain Research*, 181, 12–22.
- Stevens, M. C., Pearson, G. D., & Kiehl, K. A. (2007). An fMRI auditory oddball study of combined-subtype attention deficit hyperactivity disorder. *American Journal of Psychiatry*, 164, 1737–1749.
- Strauss, M. E., Thompson, P., Adams, N. L., Redline, S., & Burant, C. (2000). Evaluation of a model of attention with confirmatory factor analysis. *Neuropsychology*, 14, 201–208.
- Supekar, K., Musen, M., & Menon, V. (2009). Development of large-scale functional brain networks in children. *PLoS Biology*, 7(7), e1000157.
- Sweet, L. H., Paskavitz, J. F., O'Connor, M. J., Browndyke, J. N., Wellen, J. W., & Cohen, R. A. (2005). fMRI correlates of the WAIS-III Symbol Search subtest. *Journal of the International Neuropsychological Society*, 11, 471–476.
- Tau, G. Z., & Peterson, B. S. (2010). Normal development of brain circuits. *Neuropsychopharmacology*, 35, 147–168.
- Uddin, L. Q., Supekar, K., & Menon, V. (2010). Typical and atypical development of functional human brain networks: Insights from resting-state fMRI. *Frontiers in Systems Neuroscience*, 4, 1–12.
- Wechsler, D. (1997). *Wechsler Adult Intelligence Scale-III*. San Antonio, TX: Psychological Corporation.
- Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., ... Buckner, R. L. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125–1165.