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The developing brain in a multitasking world

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Abstract

To understand the problem of multitasking, it is necessary to examine the brain's attention networks that underlie the ability to switch attention between stimuli and tasks and to maintain a single focus among distractors. In this paper we discuss the development of brain networks related to the functions of achieving the alert state, orienting to sensory events, and developing self-control. These brain networks are common to everyone, but their efficiency varies among individuals and reflects both genes and experience. Training can alter brain networks. We consider two forms of training: (1) practice in tasks that involve particular networks, and (2) changes in brain state through such practices as meditation that may influence many networks. Playing action video games and multitasking are themselves methods of training the brain that can lead to improved performance but also to overdependence on media activity. We consider both of these outcomes and ideas about how to resist overdependence on media. Overall, our paper seeks to inform the reader about what has been learned about attention that can influence multitasking over the course of development.

Key works

alerting; attention; effortful control; executive attention network; multitasking; orienting; self-regulation

Introduction

A theme of this special issue is set out by the guest editor is as follows:

> "Fundamentally, the issue of multitasking in both experimental and everyday tasks is one of dividing and deploying attention resources effectively. … The basic questions that have fueled research for decades concern the processes and mechanisms that drive the deployment of attention, how they develop across childhood and the constraints under which they operate (Courage, Bakhtiar, Fitzpatrick, Kenny & Brandeau, this issue)."

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In this paper we address these basic questions and discuss how the brain networks that underlie attention develop in infancy and childhood. A central theme of the paper is that attention training and brain state training procedures can improve the efficiency of the attention networks that are central to effective multitasking. We also examine individual differences in attention network efficiency, sensation seeking, and effortful control that might influence the frequency and efficiency of multitasking. Together, these findings allow us to better understand how brain plasticity can provide opportunities to improve multitasking ability but also has the potential for excessive use of the Internet and other media.

In Section I of the paper we review the brain's attention networks (i.e., alerting, orienting, and executive control) as they relate to multitasking. In Section II we consider the development of these attention networks. During development, the connectivity of brain networks changes and these changes influence the control that individuals can exercise over their behavior. In Section III we discuss attention network plasticity and the effects of specific network training and practice (including the use of video games) on behavior. In Section IV we discuss another aspect of plasticity; how the networks can be altered through the induction of different brain states and the consequences of this for their use and overuse. The fact that training can influence specific brain networks and brain states makes it plausible that exposure to new media and the constant need to switch between tasks and to deal with the interruptions inherent in multitasking could modify certain brain circuits. Finally, in Section V the attention training framework is used to explain how the brain might change with habitual multitasking and multimedia experience and how these effects might be moderated through techniques that can alter brain states (e.g., meditation) and improve self-regulation.

I. The brain's attention networks

Neuroimaging procedures have identified the brain networks that underlie attention and these have been discussed in detail in previous publications (Petersen & Posner, 2012; Posner, 2012). These specialized attention networks include *alerting*, defined as achieving and maintaining a state of high sensitivity to incoming stimuli; *orienting*, which is the selection of information from sensory input; and *executive attention* that involves mechanisms for monitoring and resolving conflict among thoughts, feelings and behavior. The function and processing efficiency of the three networks have been assessed with the Attention Network Test (ANT), a flanker-type task in which differences in reaction time (RT) between various test conditions are used to evaluate each network (Fan, McCandless, Sommer, Raz, & Posner, 2002). The results of testing with the ANT and data from neuroimaging procedures across a wide age range indicate that the three networks engage separate brain mechanisms and are functionally independent, although there are some interactions among them in real life and in certain tasks (Fan et al 2009).

It is important to note that the single tasks that we perform consist of multiple components or operations and involve switching or resisting switching between brain areas. Neuroimaging has revealed that even the very simple task of shifting attention from one location to another activates a network of neural areas (Posner, 2012). In general, these networks consist of widely scattered nodes, often in both cortical and subcortical locations, that must be coordinated to carry out the task. For the simple and highly practiced tasks that we do this switching does not involve any major effort. For more complex and effortful tasks, and particularly when multiple tasks are involved, the executive network is also needed. Below we discuss the role of the networks in multitasking, focusing particularly on the orienting and executive attention networks.

Orienting

Multitasking typically involves aligning ones attention with alternating sources of sensory input. These sources include computers, portable electronic devices, televisions, phones, radios, books, instructions or requests from other people, or a myriad of other possible stimuli and events. All of these involve orienting to the sensory modality over which the information is transmitted. While sensory systems such as vision and audition are anatomically separate, attending to any one of them involves the same set of attentional brain areas (Petersen & Posner, 2012; Table 1). The brain network underlying orienting consists of a dorsal region including the frontal eye fields and superior parietal lobe related to endogenous or voluntary orienting of attention, and a more ventral region including the parietal-temporal junction, related to exogenous or automatic orienting induced by a signal (Corbetta & Shulman, 2002; Posner, 2012).

The following example illustrates how the orienting network functions in the context of multitasking:

As you are playing the video game Space Fortress on an iPad a door opens and before you are even aware of a visitor, your attention has moved to the door. The first thing you notice is that you are looking at the door and not at the video. You carry on a conversation with the visitor during which you decide to call a friend on your iPhone; now you orient away from the door to your phone.

How does the brain accomplish this task? We have a fairly detailed answer to this question (Corbetta & Shulman, 2002). The input from the sound made by the door opening automatically activates a set of ventral parietal pathways that connect to the frontal eye fields. Visual system cells in the frontal eye fields then work through the temporal-parietal junction to orient attention from visual to auditory input. At the same time motor cells in the frontal eye fields generate a signal that shifts the eyes and head in the direction of the sound. You suddenly become aware of being oriented to the door and not the screen. The goal of calling a friend is triggered by the conversation with the person at the door. As that goal becomes active it works through the anterior cingulate via long connections to the dorsal parietal lobe in a circuit for voluntary orienting. The temporal-parietal junction acts to break engagement with the visitor at the door and back thorough the frontal eye fields to move the eyes and via the motor system to move other parts of the body, to the phone.

This account illustrates how the brain networks involved in orienting work to provide priority to a location where a significant event has occurred or is expected to occur. Orienting may involve adjustment of the head and eyes or may be entirely covert as when you shift attention to the door while remaining fixed on the screen. Orienting may occur as a result of strong cues such as the noise of the door, or more subtle changes in luminance or motion. This automatic form of orienting is called *exogenous* because it is induced by the cue. It is also possible to orient voluntarily by choosing to move attention to a location as when locating the iPhone. This is called *endogenous* orienting. The fact that orienting can be summoned involuntarily to an event underlies our distractibility. The partial separation of voluntary mechanisms from automatic ones illustrates how voluntary goals can be involved in resistance to distraction and in the choice of where to attend.

Alerting

The orienting network is not the only brain network involved in multitasking (see Table 1). Also important is the *alerting network* that carries out the function of obtaining and maintaining the alert state. It has been associated with the locus coeruleus of the brain stem and cingulate areas as well as frontal and parietal regions of the cortex. Hebb (1949) noted that every stimulus has two effects on the brain. One is mediated by the specific sensory system activated by the signal to which attention can be oriented, and the other is through the brain stem that maintains cortical arousal. The brain stem norepinephrine system responds to warning signals to move the person from a default brain state of relative rest to a phasic alert state at the beginning of an expected event such as the appearance of a target at the start of an experimental trial (Posner, 2012). This state of alertness or vigilance helps to determine the speed of response on any trial as reaction time improves for several hundred milliseconds following a warning. However, stimuli not directly involved in a task, such as talking to a passenger while driving, may also help to maintain the alert state. In this way stimuli that are potentially distractions may help to maintain a state of alertness that actually improves performance. This could explain students’ reported use of background music to help when studying material that is not of intrinsic interest (Ruff & Rothbart, 1996).

Executive Attention

The dominant control network for older children and adults is the *executive attention network*. Executive control is needed in situations that require monitoring and resolving conflict in planning, decision-making, error detection, novel responses, and overcoming habitual actions. It serves as the mechanism whereby stored goals and intentions influence our behavior through control of shifting and focusing attention. The executive attention network is critical to multitasking in that it allows stored information related to one’s current goals to influence brain networks involved in the processing of more immediate information. It also plays a role in controlling distraction during task performance as well as in switching between tasks to be completed.

The executive attention network consists of midline frontal structures such as the anterior cingulate cortex, the anterior insula and the underlying striatum (see Table 1). The executive network also works to regulate other brain networks. It is involved in resolving competing actions in tasks where there is conflict between them by enhancing brain activity in the networks related to ones current goals and inhibiting activity in conflicting networks. This mechanism underlies what is often called self-control (in adult studies) or self-regulation (in child studies). Controls are implemented through long connections between the nodes of the executive attention network and cognitive and emotional areas of the cortex and subcortex.

Thus, the executive network is important for voluntary control and self-regulation of emotions, thoughts, and behavior (Bush, Luu & Posner, 2000; Sheth et al., 2012).

The degree to which different children and adults can voluntarily control their own behavior and emotions is an important aspect of individual differences. This ability, called *effortful control*, can be measured with self-report temperament questionnaires in adults and older children (Rothbart, 2011; Rueda, 2012). In younger children, it can be assessed with parent-report questionnaires (e.g., subscales of the Children's Behavior Questionnaire; Rothbart, Ahadi, Hershey & Fisher, 2001) and with certain standard tasks (e.g., delay of gratification; go/no-go; age appropriate versions of the Stroop task; Kochanska, Murray, & Harlan, 2000) that reflect the child's ability to inhibit a dominant response and to carry out a subdominant response. Thus, effortful control involves both inhibition and excitation of emotion and behavior. It is related to the control of impulses and the ability to carry out long-term goals (Rothbart 2011) and is one broad dimension of temperament that reflects self-regulative abilities.

The executive attention network underlies effortful control and both are predictive of children's emotional regulation in many social situations. Although immature in infants and toddlers, there is evidence of its rapid development during the preschool years (Rueda, 2012). In childhood, performance on conflict-related cognitive tasks is positively correlated with measures of children's effortful control (Rothbart, 2011). The most widely used conflict task for adults is the Stroop word-color interference task. However, as reading is not an overlearned skill in young children and provides less interference for color naming, conflict is commonly measured with a variety of other tasks (e.g., a flanker task in which conflicting elements surround the target) that activate the anterior cingulate and produce strong interference.

During childhood and in adulthood effortful control has been related to social skills, empathy, school performance, and measures of self-control have been found to predict indices of life success, including health, income, and human relationships (Moffitt et al., 2011; Rueda, 2012). It may also be related to individual differences in the choice of multitasking strategies and in the ability to multitask effectively. The executive network is critical to making switches between tasks, maintaining a focus of attention during potential distraction, and pursuing goals that underlie the human ability to engage in multitasking. The correlations between effortful control and tasks the measure executive attention also facilitates an understanding of the brain mechanisms involved in self-regulation. For example, neuroimaging studies have shown that the anterior cingulate is specialized such that the more dorsal region is connected to frontal and parietal areas and is involved in cognitive functions, whereas the more ventral areas are connected to the limbic areas and are related to emotion and detection of reward (Bush et al., 2000).

Attention switching and goal hierarchies

While the concept of multitasking initially arose in connection with computer processing, adapting the concept to human information processing activity requires considering how purposeful human behavior can be organized into a hierarchy of goals and subgoals (Carbonell, 1981). The hierarchy, often called a goal tree, typically involves one overall goal with many sub-goals. For example, making breakfast may include pouring water for coffee, toasting bread, spreading butter, etc., as components. If while making breakfast the phone rings, an entirely different goal tree involving answering, greeting and arranging an appointment may be involved. During execution of this new goal tree, the goal of making breakfast is inhibited, though it can usually be returned to at any point. The motivations and goals involved in the prioritizing of active goal trees during multitasking are diverse. These include interruption by an external or internal source, the pursuit of recreation, new information, social motivation, the need for switching away from a more difficult to an easier task, boredom, etc. The mechanism by which the goal tree affects behavior is often called a “top down” influence, while the shifts in behavior caused by external events are often referred to as “bottom up” influences. Human multitasking is highly complex, and experiments have tried to simplify the issues sufficiently that the underlying anatomy can be revealed. In the next few paragraphs we examine first very simple and then more complex tasks in order to determine their relation to the attention networks illustrated in Table 1.

One such simple task is a switch from the *resting state*, in which the person is relaxed and not performing any task, to a state of control involving executive attention. For example, Sridharan, Levitin and Menon (2008) used a variety of auditory and visual tasks that required a high degree of vigilance in order to detect a critical target. At the moment a target was presented, participants switched from a resting to an alert state oriented to the target location. Using fMRI measures the authors reported that activity in a brain circuit including the anterior insula and anterior cingulate was involved in carrying out the switch from resting state to the state of focused attention needed for target detection. These sites are part of the executive attention network. The authors identified the right insula cortex as being critical in carrying out this relatively simple switch.

We now consider switching between tasks. The most common design in studying task switching has been to define two tasks that rely on a common set of stimuli (e.g. stimuli that can be classified either on the basis of either color or shape) and then to present a signal to indicate when a switch between the color and shape classification is required (Jost, Mayr & Rosler, 2008; Monsell, 2003). A number of methods, including lesioning in macaque monkeys (Rushworth, Hadland, Gaffan, & Passingham, 2003), and in humans by creating a temporary lesion by transcranial magnetic stimulation (TMS) (van Schouwenburg, O’Shea, Mars, Rushworth, & Cools, 2012), or by electrical recordings from the scalp (EEG) (Rushworth, Passingham & Nobre, 2002; Taylor, Nobre, & Rushworth, 2007) have identified a critical circuit involved in the switch. This circuit includes the anterior cingulate cortex and adjacent medial prefrontal cortex and areas of the striatum, particularly the putamen. The anterior cingulate is closely connected to the anterior insula both during task performance and when the person is at rest, so the results when switching between two tasks can be seen to build on and expand the brain areas involved in switching from the resting to the active attentive state.

However, the simple switch between highly similar tasks does not do justice to the complexity of switching within the hierarchically organized elements of a task and between tasks related to one goal and those related to a completely different goal. Consider a task that involves a hierarchy of goals like preparing breakfast: with subtasks of pouring water, making coffee, adding cream, toasting bread and spreading butter. This task captures some of the hierarchical nature of human activities. During an fMRI scan the breakfast task was simulated by a string of letters presented on a computer at a rate of about 5 seconds per letter (Farooqui, Mitchel, Thompson & Duncan, 2012). Participants were to detect letters making a three-letter word (e.g., CAT) that changed on each trial, followed by detection of a single fixed letter X. If the letter X occurred prior to completion of the word it was not a target. Thus the lowest level of the task was detecting the first two letters of the word (C and A). The next level was completion of the word (e.g., the letter T which completed the word CAT, simulating finishing the toast). The highest level was detecting the X (i.e., completing the whole breakfast). Target switching at all levels (e.g., from C to A) showed activation in the core areas of the insula and cingulate. However, when the letter indicated the completion of the subgoal (e.g. the T in CAT) or entire task (finding the X after completing the word CAT), fronto-parietal areas were also active, and activity in all areas increased markedly. Targets related to completion of the overall goal had the most widespread and strongest brain activity.

Task switching includes switching to a new goal as well as moving between various sub-goals. When dinner is called, the child may take more or less time to switch away from his or her activities. Depending on whose point of view you adopt, the child is either being distracted from the call to dinner by continuing the activity or showing persistence in completing the task. While no single imaging study has completely captured natural, everyday multitasking, considering the literature as a whole, the brain areas and their connections required for multitasking become relatively clear. The core set of areas includes the anterior insula, anterior cingulate and connections to the underlying striatum. These are all areas of the executive network.

As the task becomes more complex and hierarchical in nature, connections to widespread parietal and frontal areas become involved. It is important to note as outlined by Farooqui et al. (2012) that the mental plan (or goal tree) that individuals use needs to be considered in interpreting neural activity related to any individual target, since the overall plan of behavior is an important determinant of the extent of involvement of all brain areas. The mechanisms underlying the adult ability to switch between complex tasks in order to pursue alternative or changing goals develops over a long period of infancy and childhood.

In summary, switching between tasks poses two difficulties for the multitasker. One of these difficulties is to maintain separate goal trees so that interference is minimized and the components of the two tasks don’t get confused. The second is to be able to switch back and forth between tasks in order to accomplish both goals. Resolving these two sources of difficulty involves the executive attention network. In addition, if one or more of the tasks involve taking in new sensory information in order to accomplish a goal, the orienting network will also be involved. Finally, as the ability to carry out multitasking effectively can also vary with the time of day and one’s level of fatigue, the alerting network will also be important for success. In the next section we describe developmental brain changes that underlie the ability to switch between tasks and to control distractions and impulses.

II. Development of attention and control

In infancy the orienting network is fairly well developed and can guide the child to critical sources of information that are important for early learning (Posner, 2012; Posner, Rothbart, Sheese, & Voelker, 2012). For example, we tend to look toward the eyes of a person with whom we are engaged in conversation. Such eye contact is important for communication and is fostered in early infancy by the relatively high spatial frequency information provided by the eye region that serves to lock the infant's gaze to that of the speaker. However, between 4 and 12 months of age the infant begins to look more frequently at the caregiver's mouth (Lewkowicz & Hanson-Tuft, 2012). This time frame is critical for speech perception and production (e.g., discriminating among native and non-native phonemes; canonical babbling), and the infant orients to the speakers mouth accordingly (Kuhl, 2010; Werker & Tees, 1999). After about 12 months, when infants are learning new words, they tend to orient toward the objects to which their caregiver attends (joint reference; Baldwin, 1991). In this way, the orienting of attention facilitates visual engagement in the early months of life, the learning of phonemes and other regularities of speech later in the first year, and object names during the second year. In addition, the ability to orient attention to a visual stimulus provided by an adult can produce a powerful soothing effect on distress in infants as young as 3 months of age (Harman, Rothbart, & Posner, 1997). A major accomplishment of a child's early life is to develop the means to achieve this stress regulation through orienting on their own (Rothbart, Ziaie & O'Boyle, 1992).. These examples illustrate the importance of attention control by the orienting network in the early months and suggest that infants are especially susceptible to control from external input.

The core network in the control of voluntary behavior in older children and adults is the executive attention network. This brain network has been studied extensively and it has a key role in establishing the priority of other networks' activity in real time (Posner, 2012; Posner & Rothbart, 2007a, b). Early signs of the emerging ability to manage conflict can be seen late in the first year of life as infants begin to perform correctly on the A-not-B task by inhibiting the prepotent tendency to respond to the trained hiding location (A) and successfully reach to the new location (B) (Diamond, 1985). There is also evidence that even younger infants are sensitive to conflict and can detect errors on certain cognitive tasks at 7 months of age. Wynn (1992) examined the development of number knowledge using a preferential looking paradigm and showed that infants looked longer at apparent errors in simple addition and subtraction. Subsequently, Berger, Tzur, and Posner (2006) used high-density electrical recording to show that detecting an error on this task involved the same frontal brain areas in infants that have been identified in adults' executive attention. However, it is not until at least 3 years of age that children begin to show regulation of their behavior following an error on a version of the Simple Simon task by slowing their next response, in the way that adults do (Jones, Rothbart, & Posner, 2003). Other developments in executive attention have also been observed during the third year of life using a spatial task in which a conflict occurs between an object's identity and its location (Gerardi-Caulton, 2000). Children between 3 and 4 years old showed reduced accuracy and slowed reaction times for spatially incompatible compared to compatible trials, likely a reflection the time it took to resolve conflict. In addition, differences in children's performance on the spatial task were correlated with parent reports of effortful control, a characteristic that continues to grow substantially across the preschool years (Rothbart, 2011; Rueda, 2012). These findings are consistent with data from fMRI showing that performance on a flanker task improved between 4 and 8 years of age coincident with the increased size of the right anterior cingulate (Fjell et al., 2012).

Network efficiency

While all humans have the same brain networks, there are individual differences in the efficiency with which those networks function. The Attention Network Task (ANT) has been used to examine these individual differences among children and adults in each of the three attention networks (Fan et al., 2002). The ANT is a flanker task in which a central target arrow is surrounded by arrows that point in the same (congruent) or the opposite (incongruent) direction. The person’s task is to press a key that signals the direction in which the target arrow points. If the flankers point in the same direction as the central arrow, reaction times will be faster than if they point in the opposite direction, providing a measure of the time to resolve the conflict induced by incongruent flankers, and hence serving as a measure of the efficiency of executive attention. Warning signals prior to the target that direct the person’s attention to where and when the target will occur also allow measurement of the efficiency of the orienting and alerting networks. A child-appropriate version of the ANT uses the same task but substitutes fish for the arrows in order maintain motivation and to provide a better story for the child who then “feeds the fish” and is given feedback on each trial (Rueda et al., 2004).

The development of executive attention has been examined using the flanker part of the ANT. In research with children from the age of 4 years and up to young adulthood, substantial improvement in the efficiency of executive attention (i.e., conflict resolution) has been found between 4 and 8 years of age but no significant development has been noted beyond that age (Checa, Castellanos, Abundis-Gutierrez, & Rueda, 2014; Rueda et al., 2004). However, overall reaction time on the ANT, as in other tasks, continued to improve until adulthood. This is consistent with the results of a study using fMRI with 735 individuals from 4 to 21 years of age in which a relationship between the ability to resolve conflict in a flanker task and the size of the right dorsal anterior cingulate was reported in children between 4 and 8 years (Fjell et al, 2012). Beyond that age, overall reaction time continued to improved due to more efficient connectivity between the anterior cingulate and other brain areas. This study is consistent with the idea that specific improvement in executive attention occurs up to about 8 years of age because of changes in the size of the anterior cingulate and after that, increased connectivity between the anterior cingualte and other brain areas mediates the improvement in overall reaction time.

Longitudinal study

We began a longitudinal study of infants when they were 7 months of age and have now followed them to age 7 years by which time they were able to carry out the Attention Network Test (ANT) (Sheese, Rothbart, Posner, White, & Fraundorf, 2008). The purpose of this study was to trace the development of attentional control across infancy and childhood. Because infants were not able to carry out voluntary attention tasks such as the ANT, a visual search task was used in which a series of attractive stimuli appeared on the screen in a repetitive sequence (Clohessy, Posner & Rothbart, 2001; Haith, Hazan & Goodman, 1988). Infants oriented to the stimuli by moving their eyes (and head) to the location. On some trials the infants showed that they anticipated what was coming by orienting prior to the appearance of the stimulus. We thought that the presence of these voluntary anticipations might be an early manifestation of the executive network. Consistent with this, we found that infants who made the greatest number of anticipatory eye movements also exhibited a pattern of cautious reaching toward novel objects that predicted effortful control in older children (Rothbart, Ahadi, Hershey, & Fisher, 2001; Rothbart, Ellis, Rueda, & Posner, 2003). In addition, these infants showed more spontaneous attempts at self-regulation when presented with potentially fear-inducing objects (Sheese et al., 2008).

We retested and genotyped the children at age 18 to 20 months and tested them again at ages 4 and 7 years when they were able to perform the flanker part of the ANT as a measure of executive attention. We found that the early self-regulatory behaviors measured in infancy and toddlerhood were related to their later orienting network scores rather than their executive network performance on the ANT (Posner et al., 2012). In infancy, children’s sustained orienting of attention was also related to lower expressions of negative affect, and higher positive affect. By age 18 to 20 months orienting was no longer related to affect, whereas later in childhood effortful control and executive attention were related to lower negative affect (Rothbart, 2011). These results may reflect the close integration of the two networks in the control of affect and behavior during early development that has been noted in fMRI studies (Dosenbach et al., 2007).

These findings led us to conclude that the orienting network provides a primary regulatory function for negative and positive affect during infancy. Later in childhood the executive attention network comes to dominate the regulation of emotions and thought, though the orienting network continues to serve as a control system (Isaacowitz, 2012; Posner et al., 2012; Rothbart, Sheese, Rueda, & Posner, 2011). The remarkable shift from caregiver control to self-control and the increased ability to serve stored personal goals that also occurs between infancy and childhood are likely consequences of this change in the role of the underlying brain networks. The parallel operation of the two networks is consistent with evidence that in adults the frontal-parietal network controlled task behavior at short time intervals, whereas the cingulo-opercular network exercised strategic control over longer intervals (Dosenbach et al 2007). Orienting tasks most often involve short intervals, such as in visual search, while higher-level more strategic control involves the executive network.

The evidence that cognitive and emotional control systems arise as part of the orienting and later the executive attention networks contrasts with other views of cognitive development that see self-control as arising out of the child’s ability to employ language to implement control (Luria, 1973; Vygosky, 1934). While language does play an important role in cognitive development, we have observed that infants use orienting to deal with distress (Rothbart, Ziaie, & O’Boyle, 1992). They show significant soothing when oriented to new stimuli but return to their previous levels of distress when orienting is disengaged (Harmon et al., 1997). We have also observed 3 to 4 year old children as they attempted to exercise control of dominant but incorrect responses in Simple Simon type games by using physical actions such as sitting on their hands or holding one hand with the other, rather than self-instruction by language (Jones et al., 2003). In addition, the significant growth of the right rather than the left anterior cingulate in self-regulation (Fjell et al., 2012) and the association of early self-regulation with orienting support a separation of control from language. Previous work may have failed to recognize the separate evolutionary development of attention systems as a basis for control, placing too much emphasis on language as a uniquely human control system.

Development and connectivity

Our studies have shown that the primary node of the executive attention network is the anterior cingulate, and error detection data have indicated that this structure is functioning in infants by 7 months of age (Berger et al., 2006). Although the network is active in infancy, it does not play as strong a role in the control of behavior as it does later in childhood because the necessary brain connectivity is incomplete and develops only slowly across the preschool years. Consequently, the control of behavior that leads older children and adults to slow down their next response after they have made an error does not occur until 3 years later (Jones et al., 2003). During those intervening early years the developing executive system continues to become connected to the many additional parts of the brain that provide the basis for the control of voluntary behavior (Fair et al., 2009).

Many of the early behavioral and MRI studies began with children of about 3 or 4 years of age. Before that age it was difficult for children to follow instruction and carry out reaction time tasks that assessed conflict. In addition, parents were unable to rate children’s effortful control and self-regulation during infancy because it was the parent who carried out most of the regulation for them (Rothbart, 2011). However, it is now possible to trace the changes in brain connectivity that occurs during early development by examining brain activity during its resting state (rsMRI; Raichle, 2009). Resting state methods can be applied at any age because they do not require use of a task. One of the brain networks that is known to be active during rest is the executive attention network (Dosenbach et al., 2007; Fair et al., 2009). Studies have shown that the frontal midline nodes of the executive attention network are present during the first few months of life (Gao et al., 2013), though connectivity with other brain structures is sparse. A significant increase in connectivity is evident by 2 years of age (Gao et al., 2009) and this continues to develop slowly across the childhood years (Fair et al., 2009). For example, during infancy and early childhood most brain networks involve short connections between adjacent brain areas, but long connections important for self-regulation develop slowly over childhood (Fair, et al., 2009; Gao, et al., 2009).

These findings suggested that the control structures related to executive attention may be present in infancy but do not exert full control over the other networks until later. Indeed, the pattern of connections observed suggests that early in life the anterior cingulate might have stronger connections to the orienting network and only later becomes differentiated from it. That is, the orienting network may play a role similar to the one later associated with the anterior cingulate. The studies on error detection and response to error seem to fit with the delay in connectivity of the anterior cingulate (Berger et al., 2006; Jones et al., 2003). Taken together, the data on resting state connectivity and from questionnaire and behavioral measures strongly indicate the role of orienting as a control mechanism by 6 to 7 months of age and executive attention as the emerging regulatory mechanism by 18 to 20 months. It seems likely that the parallel activity of those two networks begins in infancy and continues into adulthood. For example, the strong tendency of adults to look away as a self-regulatory strategy suggests a continued role of the orienting network for adults.

Individual Differences in Attention Control

During development, brain activations that occur during task performance become more focal and the maturation of long connections allow for more efficient connectivity between brain regions (Posner & Rothbart 2007b). However, certain individuals have more focal activations and more efficient connectivity than others and are therefore better able to exercise the various functions of self-regulation, including shifting and focusing of attention and resisting distraction. Moreover, childhood assessments of self-control (Moffitt et al., 2011) and self-regulation (Casey et al., 2011) have predicted income and overall health and welfare in adults. How do these individual differences arise? In part they are due to genetic variation. However, environmental influences and learning also lead to differences in efficiency; experience and genetics interact. Accordingly, the expression of genes can be altered by the environment in which the genes operate and likewise, genes can influence the degree to which behavior is altered by experience (Belsky & Pluess, 2009; Spector, 2012).

We have pursued two strategies to examine how genes are related to individual differences in the efficiency of the attention networks. One approach has been to associate the attentional networks with particular neuromodulators based on data from neuroimaging, lesion studies, pharmacological manipulations, and behavior genetics (Green et al., 2008; see also Table 1). These associations have led to the identification of candidate genes that were predicted to be related to each network. Many genes exhibit a number of relatively high-frequency variants that can code for different physical configurations and these in turn can alter the efficiency of a network. In some cases it has been possible to relate these differences to individual performance on tasks involving brain networks (Fossella et al., 2002). For example, individuals with different alleles of two genes related to dopamine (DRD4, MAOA) showed differences in their ability to resolve conflict on the ANT and also produced different activations in the anterior cingulate, a major node of the executive attention network (Fan et al, 2003). However, other results have qualified this view somewhat. It seems clear, for example, that serotonin as well as dopamine can influence the executive attention network (Reuter, Ott, Vaitl, & Hennig, 2007) and that there are interactions between dopaminergic and cholinergic genes at the molecular level that modify the degree of independence between them (Market, Montag, & Reuter, 2010). Nonetheless Table 1 provides a viable scheme for organizing and predicting genetic influences on attention, cognition and behavior.

A second approach has been to examine the effect of genetic alleles on variations in behavior during development. One version of a dopaminergic gene shown in Table 1 that influences the executive network (the 7-repeat allele of the DRD4 gene) may play an important role in multitasking behavior. For example, a common characteristic of multitaskers is a high level of sensation seeking (Jeong, & Fishbein, 2007). Sensation seeking is a temperament or personality trait involving the search for experiences and feelings that are “varied, novel, complex and intense”, and by the readiness to “take physical, social, legal, and financial risks for the sake of such experiences.” (Jeong & Fishbein, 2007, p. 368). This trait has also been related to the presence of the 7-repeat allele. Thus the presence of the DRD4 gene may be an important factor in the type of individual who prefers to multitask.

How does high sensation seeking develop? We illustrate the complex interaction between genetic variation and environmental influence on this trait with results from our longitudinal study (Sheese, Voelker, Rothbart, & Posner, 2007) that involved the 7-repeat allele of the DRD4 gene. This allele has been associated with attention deficit/hyperactivity disorder (ADHD) as well as with the temperamental quality of sensation seeking. In our longitudinal study, cheek swabs were used to collect DNA samples and genetic variation was identified in twelve genes that had been related to attention in studies with adults (Sheese, et. al., 2007). The children had been evaluated when they were 7 months old, and genotyping took place when they returned to the laboratory at 18 to 20 months of age. In addition, parenting quality was examined through observation of caregiver-child interactions in which the children played with toys in the presence of one of their caregivers. Raters reviewed videotapes of the interaction and rated the parents on five dimensions of parenting quality according to a schedule developed by the NICHD Early Child Care Research Network (1993). This measure indexes support, autonomy, stimulation, lack of hostility, and confidence in the child.

According to their scores, parents were divided at the median into two groups: one showing a higher quality of parenting, and the other a lower quality. The results showed an interaction between parenting quality and variation of the DRD4 gene in children’s level of sensation seeking. Our measure of sensation seeking aggregated parent report temperament scales for activity level, impulsivity, and high intensity pleasure seeking. For children with the 7-repeat allele, there was a strong influence of parenting quality. Children with both the 7-repeat allele and lower quality parenting were high in our sensation seeking measure. Those with higher quality parenting and the 7-repeat allele were about average in sensation seeking. Children without the 7-repeat allele showed about average levels of sensation seeking regardless of parent quality.

Because the anterior cingulate is important in executive attention and also in reward and punishment networks, we expected that the 7-repeat allele influence on sensation seeking might be mediated by executive attention. However, in the study by Sheese et al. (2007), data showed that at 18 to 20 months there was no influence of the 7-repeat allele on executive attention. Rather, the genes and environment interacted to influence sensation seeking as observed by the caregiver. However, the same children at age 4 years did show an interaction between the presence of the DRD4 7-repeat allele and parenting quality in determining effortful control, and this effect has been replicated in other studies (Sheese, Rothbart, Voelker, & Posner, 2012; Smith et al., 2012). Since effortful control is linked to executive attention, this finding suggested that the executive network could be a mechanism for the widespread effects of Gene x Environment interactions, at least in older children and adults. Thus the DRD4 7-repeat allele may operate through executive attention only after age 4 years when executive attention is sufficiently well developed.

III. Network plasticity: Attention network training

In the previous sections we have provided evidence that switching between tasks involves the executive attention network including the anterior cingulate and anterior insula. This brain network assumes dominant control of behavior by middle childhood (Posner et al., 2012; Rothbart et al., 2011). There is strong documentation of at least two types of change in this network during early development; an increase in the amount of grey matter in the right anterior cingulate and an increase in anterior cingulate connectivity to other brain areas. After age four years, the change in connectivity is central to improvements in reaction time on a variety of conflict tasks (Fjell, et al., 2012). These results provided evidence of plasticity in the network during childhood and both types of change resulted in improved efficiency in children's ability to resolve conflict and carry out other functions of the executive attention network.

Training task switching

Can we find similar changes in brain plasticity in adulthood? An important series of studies by Bavelier, Green, and colleagues (for a review see Bavelier, Green, Pouget, & Schrater, 2012) compared participants who were high or low in their frequency of playing action video games. Action video games require concentration on pursuing a single goal (or switching between different goals) with many sub-goals that require constant prediction and updating in the presence of distractors. As such, action video games can be considered analogous to real world multitasking. Collectively, the studies showed that high frequency compared to low frequency video gamers had better basic vision skills (e.g., contrast sensitivity, tracking, peripheral sensitivity), faster reaction times, and greater improvements in tasks that required the dorsal portion of the orienting network, such as target detection (Bavelier, Achtdman, Mani, & Focker, 2012). High video game players were also better at tasks that required sustained attention and divided attention (Green & Bavelier, 2003) and were more effective in ignoring distraction, particularly during high perceptual processing loads. Similar effects were found when a group of randomly selected participants were tested before and after training sessions in which they learned to play and practice with video games. These before and after measures showed that playing action video games was the cause of improvements in orienting to relevant visual stimuli and not merely a correlate.

Neuroimaging research extended these findings on the effects of action video gaming. For example, an fMRI study showed that those high in video game playing did not show increased brain activity in the fronto-parietal component of the orienting network as task difficulty increased, while novices did show such an increase (Green, Sugarman, Medford, Klobusicky, & Bavelier, 2012). However, as task difficulty increased, additional network components that included the anterior cingulate were also recruited. This might mean that the lower activation in the gamers'orienting network was due to their having developed more efficient allocation of attention resources as a result of their gaming. The results of another study of high and low video gamers in which electrical recording and a different type of target detection task were used, indicated that the advantage of those trained on video games lay in their enhanced ability to filter irrelevant information (Mishra, Zinni, Bavelier, & Hillyard, 2011). They also found that high gamers showed larger P300 reactions to task information than did low gamers. Since P300 is an index of novelty detection and is elicited by conflict resolution between the target and irrelevant distractors (Dien, Spencer, & Donchin, 2000; Donchin, 1981), the finding indicated that components of the executive attention network were also recruited during task performance. This suggested that video game training led to changes in executive attention as well as in the orienting network. Consistent with this, Shulman et al. (2009) found that when a novel stimulus appeared during an orienting task the anterior cingulate was activated indicating that the executive attention network was also involved. Overall, the studies of action video game practice showed that training adults on the games lead to improvement in the efficiency of the orienting network and to a lesser degree the executive network.

Recent studies of individuals playing action video games showed that there was a transfer from game playing to task switching, a process that involves the executive attention network (Cain, Landau, & Shimamura, 2012; Chiappe, Conger, Liao, Coldwell, & Vu, 2013; Strobac, Frensch & Torsten, 2012). Most of these studies examined switching between two tasks and compared either groups of high versus low video game players or groups that were tested before and after training in video games. In general, the more exposure to video games, the faster and more reliable was the switching between tasks. Because the same participants were tested before and after training in comparison to an active control condition, evidence was provided for a causative role of the video game training in the transfer effect (Green et al., 2012). However, much of the observed improvement was in overall reaction time, and when this was controlled, the direct effect of training on task switching itself was modest. Overall, the evidence from several studies indicated that there was a large and consistent effect of video games on aspects of orienting, particularly in blocking irrelevant information, and a much smaller effect on task switching and the executive network. Green et al. (2012) summarize these effects as follows:

> “The impact of training on the interpretation of the change in task-switch cost is worth considering carefully… to the extent that action video games can indeed reduce task-switch cost, the effect seems less robust than the previously seen effects of action video games on various aspects of visual attention and low-level vision” (p. 992)

It should also be noted that a number of studies have shown that video game training does not always lead to improvement in performance, and may even have a negative effect on certain executive attention tasks (Bailey, West & Anderson, 2010; Powers, Brooks, Aldrich, Polladson, & Alfieri, 2013). While the issue remains open, it seems clear that the primary effect of video game training is on the orienting of attention with a more modest effect on the executive attention network (but see Strobach et al., 2012).

Since the everyday multitasker regularly switches attention between one activity or media source or window and another, one might expect that, like action video game players, this practice would enable heavy multitaskers to be successful at task switching. However, the results of one study cautioned against this simple view and indicated that individual differences in the choice of multitasking in real world situations is an important consideration in addition to training effects on laboratory tasks. In a study with Stanford undergraduates, Ophir, Nass, and Wagner (2009) found that self-reported heavy compared to light media multitaskers were more distractible and performed more poorly on a number of cognitive tasks, including selective attention and task switching. A later study (Minear, Brashev, McCurdy, Lewis, & Younggren, 2013) showed no difference in attention between those high and low in media multitasking. These findings seem paradoxical; if training improves orienting and executive attention in action video gamers why does it not produce similar advantages for high media multitaskers who have had extensive real world practice in task switching?

There might be several reasons for this. One is that those students who were lower in attentional control might be more attracted to multitasking as a work strategy. Lin (2009) suggested that media multitaskers have a cognitive style that includes a “greater breadth of attention” rather than one in which they attend to the information that is relevant to one task at a time. Moreover, as Jeong and Fishbein (2007) reported, multitaskers were often found to be high in sensation seeking, defined as seeking out novel information and experience. Sensation seeking is partly related to the dopamine 4 receptor gene and is over-represented in the population of individuals with ADHD. It may well be that certain media multitaskers have a low level of attentional control and their choice of heavy media multitasking may reflect in part the difficulty they have in concentrating on a single task or source of information. While multitasking could provide effective training on task switching for some individuals, this effect would be constrained by the tendency of those with poor attention skills to also choose multitasking. Consistent with this, a recent study by Sanbomnatsu, Strayer, Medeiros-Ward, and Watson (2013) showed that undergraduates who self-reported as high compared to low6 real-world multitaskers had lower working memory capacity (see Manytla, 2013), were more impulsive and sensation-seeking, and were highly confident on their ability to multitask effectively. However, these individuals in fact scored more poorly on actual tests of multitasking. Additional studies with a larger and more diverse set of participants are clearly needed in order to be sure that the paradox of multitasking leading to reduced ability to switch between tasks is accounted for by lower executive attention efficiency among those choosing to multitask. Finally, not all media and multimedia activities are equivalent to action video games in the skills that are acquired. Green et al. (2010) noted that action video games are those with high velocity target movement, the presence of many objects that are transiently visible, convey spatial and temporal uncertainty, and have high perceptual, cognitive and motor load.

Training executive attention

Multitasking depends on the use of many brain networks both in its execution and through the characteristics of individuals who choose to multitask. Two of the most important networks are those that underlie executive attention and the network related to working memory. These two networks overlap because working memory involves control by executive attention (Baddeley, 2007). Studies have shown that the efficiency of these brain networks can be improved in children and adults through practice on working memory tasks (Buschkuell, Jaeggi, & Jonides, 2012; Jaeggi, Buschkuell, Jonides, & Perrig, 2008; Olesen, Westerberg, & Klingberg, 2004; Westerberg, & Klingberg, 2007) or by attention training

(Miller et al., 2012; Rueda, Roth, McCandless, Saccomanno, & Posner, 2005; Rueda, Checa, & Combita, 2012). In general, improvements to these networks are evident either in an increase in the brain area given over to a particular function, the tuning of neurons within that brain area so that they perform more efficiently, or changing the efficiency of white matter pathways that connect areas of the network. When the trained network involves a general function such as attention or working memory, increased efficiency could produce improvement in (and possibly preferences for) many different tasks that use all or parts of that network.

In many of these studies, changes are measured not only by task performance but also by changes in the efficiency of the brain networks involved. In one study, 4- to 6-year-olds were given a 5-day training intervention using computerized exercises designed to train attention in general and to improve their ability to resolve conflict in particular (Rueda et al., 2005). Evidence from scalp electrodes showed clear evidence of improvement in network efficiency in resolving conflict. Trained 6-year-olds showed more adult-like responses from electrodes placed over midline frontal areas associated with the dorsal anterior cingulate (Dehaene, Posner & Tucker, 1994). In 4-year-olds, training seemed to influence the more anterior electrodes that have been related to the emotional control areas of the cingulate. The trained group also showed improvement on a measure of IQ compared to untrained control children.

A replication and extension of this study with 5-year-olds showed the same pattern of EEG change following training, improved IQ scores, and beneficial effects on performance of tasks that required affect regulation and delay of gratification (Rueda et al., 2012). A study with adults showed similar electrical changes following three days of exercises appropriate for training attention in adults (Millner et al., 2012). These studies suggest that practice-oriented training can produce changes in midline frontal areas that have been related to executive attention and self-regulation (Diamond & Lee, 2011; Rueda et al., 2005). Several other studies have been shown to improve attention in preschool children (Diamond, Barnett, & Monroe, 2007; Rueda et al., 2005, 2012) and some of these involved classroom training. For example a yearlong study using Tools of the Mind, a curriculum designed to improve executive function showed large changes in tasks that measure the ability to resolve conflict. Working memory training, which overlaps heavily with executive attention, has led to improvements in the performance of children with ADHD (Klingberg, Frossberg, & Westerberg, 2002). Although there are few studies of the effectiveness of training on everyday multitasking, it may be that the requirement for task switching strengthened by action video gaming could also be strengthened by other direct practice exercises that target working memory and executive attention networks.

IV. Network plasticity: Changing brain states

We have reviewed studies showing that brain activation and connectivity can be altered by practice on a particular task. For example, practice on action video games changes activation in the orienting network and also improves the time to switch between tasks. We called this form of plasticity attention network training. The goal of this training has been to use repetitive practice on a specific task (e.g., attention, working memory, visual discrimination) to alter specific networks related to those cognitive tasks. Another way to influence brain activation and connectivity is to change the state of the brain (Tang & Posner, 2014). A brain state is the reliable pattern of brain activity that involves the activation and/or connectivity of multiple large-scale brain networks. The idea of a change in brain state goes back to evidence that activity in the reticular system of the brain stem and thalamus modulates the state of cortical reactivity (Moruzzi & Magoun, 1950). Since the time of that research, brain states such as sleep or wakefulness have been related to the activity of neuromodulators and have been widely studied in both animals and humans. Rather than using a specific cognitive task to train networks, state training uses more general procedures (e.g., meditation) to develop a brain state that can influence the operation of many networks (see Tang & Posner, 2014).

Training the central and autonomic nervous systems

Recently there has been growing interest in the specification of brain states, due mainly to the fMRI studies that can trace connectivity of brain networks during the resting state (Raichle et al., 2001; Raichle, 2010). As noted previously, the networks that are active during the resting state include the medial prefrontal cortex (mPFC), anterior cingulate cortex, and posterior cingulate cortex – often called the Default Mode Network, along with a number of other areas that are also active and correlated when at rest (Gusnard & Raichle, 2001; Deco, Jirsa, & McIntosh, 2011). Changes in brain state involve widespread effects on brain activity that include both cortical and subcortical areas and involve the autonomic as well as the central nervous system. Training methods that appear to alter brain state are varied and include hypnosis, meditation, and physical exercise (Raz & Buhle, 2006; Kramer & Erickson, 2007; Holzel et al., 2011). In this paper we concentrate on meditation because it has been studied in the most detail.

One of the main advances in studies of meditation has been the ability to change performance and alter brain mechanisms using short-term training (Tang et al., 2007; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010; Leiberg, Klimecki, & Singer, 2011). One way to accomplish this rapid change is a form of meditation called Integrative Body Mind Training (IBMT), a meditation technique based in ancient Eastern contemplative traditions that involve achieving a state of restful alertness and a high degree of awareness and balance of body, mind, and environment. Specific techniques to accomplish this goal involve music, mental imagery, body relaxation, and mindfulness. The ability of IBMT to produce a meditation state with five days of training (20 minutes per session) has made it possible to examine the changes that occur over time. These studies involved random assignment of participants to IBMT or a control group trained in conventional muscle relaxation (Allen et al., 2012; Tang et al., 2007, 2009, 2010; Tang, Rothbart, & Posner, 2012). There is evidence that a child version of IBMT can also be used to train children as young as 4 years of age (Tang, Yang, Leve, & Harold, 2012).

In a series of studies with college students, a comparison between the IBMT and a relaxation control showed improved executive attention, mood, and stress regulation in the IBMT group and increased activity and connectivity in the anterior cingulate, striatum, and anterior insula compared to controls (Tang et al., 2007, 2009, 2010, 2012; Holzel et al., 2012). The measures of connectivity were taken using diffusion tensor imaging (DTI) under standard resting conditions before and after training. The results showed that connectivity increased in efficiency in all of the pathways that led to and from the anterior cingulate.

The central (CNS) and autonomic nervous (ANS) systems work together to maintain body and mind states (Lane et al., 2009). ANS activity is a biomarker for monitoring meditative states, including heart rate, skin conductance response (SCR), and respiratory rate and amplitude (Wallace, 1970; Tang et al., 2009). During and after 5 days of training, both the IBMT and relaxation groups showed positive changes in these biomarkers of autonomic activity. However, the IBMT group also showed significantly lower heart rate and skin conductance, increased belly respiratory amplitude, and decreased chest respiratory rate than the relaxation control group. These results reflected improved ANS regulation during and after IBMT practice as compared to traditional relaxation training (Tang et al., 2009). Heart rate variability (HRV) is a noninvasive technique that allows for a reliable and accurate measure of sympathetic and parasympathetic autonomic functions. High-frequency HRV is related to parasympathetic function (Pumprla, Howorka, Groves, Chester, & Nolan, 2002; Tang et al., 2009). The significant increase of high-frequency HRV in the IBMT group during training indicated successful inhibition of sympathetic tone and activation of parasympathetic tone in comparison with the relaxation-training group. This result is consistent with previous findings of decreased sympathetic activity and increased parasympathetic activity during several forms of meditation (Wallace, 1970; Tang et al., 2009).

Physical changes in connectivity

The changes in functional connectivity that occur during development and that have been documented in resting state MRI studies are based on correlations between blood-oxygen-level-dependent (BOLD) activity in separate brain areas. Is there evidence of actual physical changes in the white matter thought to underlie these correlations? Our work with adults has uncovered white matter changes using diffusion tensor imaging (DTI) that have similarities to those found during development. Therefore, training studies with adults might be useful in understanding how the connections that develop during childhood support the changes in self-regulation that have been observed between infancy and adulthood.

During development there is a significant change in the physical connections between brain areas. The number of axons that connect brain areas increases and this is followed by an increase in the myelin sheath that surrounds the axon and provides insulation. Together these changes result in more efficient connections between brain areas. Fractional anisotropy (FA) refers to the directionality of the diffusion of water molecules and is the main index for measuring the integrity of white matter fibers when using DTI. In our work with college students we studied FA before and after IBMT in comparison to a control group given the same amount of relaxation training. We found clear improvement in the executive attention network after only five days of training. After two to four weeks we found significantly greater change in FA following meditation training than following the relaxation training control in all areas of connectivity of the anterior cingulate, but not in other brain areas (Tang et al., 2010).

In summary, meditation training can change brain state. This changed state can yield improved executive attention, increased positive mood, and reduced stress. It provides increased dominance by the parasympathetic branch of the autonomic nervous system and increased connectivity between the anterior cingulate and the striatum as well as other brain areas. The question of whether meditation training could influence multitasking performance has not been addressed, although given their joint link to the executive attention network, such a relation might reasonably be predicted.

V. Altered brain states, multitasking, and excessive use of media

Although it is possible that multitasking might become more efficient following either attention network or attention state training, there is substantial concern that adolescents and young adults, who are the biggest users of the Internet and most likely to engage in media multitasking, could become addicted to those platforms and less able to carry out tasks that require sustained attention. Although such an Internet addiction has not been identified as a psychopathology in the most recent American Psychiatric Association Diagnostic and Statistical Manual of Mental Disorders (DSM-V), there is substantial public interest in the consequences of compulsive multimedia overuse. Indeed, excessive media use is acknowledged to be a growing mental health concern and is often co-morbid with other conditions such as depression, compulsive behavior, social anxiety, and ADHD, although the direction of causality has not been established and is a topic of ongoing research (Ko, Yen, Yen, Chen & Chen, 2010).

Links to addiction

Although not identified as an addiction in the DSM-V, there is good evidence that the excessive use of multiple media formats, especially as accessed by the Internet, can be a source of dependency or compulsive behavior (Young & Cristiano, 2010). Indeed, excessive Internet use is considered to be an addiction in some parts of Asia and Europe when the individuals affected also show (a) withdrawal signs when the computer is not available, (b) tolerance leading to even greater use, and (c) negative achievement and lifestyle repercussions (Block, 2008; Hong et al., 2013). The divergence of opinion appears to rest on the distinction between Internet excess as a psychiatric disorder with addictive potential in its own right, and Internet excess as a problematic behavior only indirectly in relation to other specific compulsive online activities such as gambling or gaming, shopping, sexual preoccupation, or email/text messaging (Block, 2008; Hong et al, 2013).

A recent summary of research on addiction (Volkow & Bailer, 2013) indicated that various forms of drug, alcohol, and tobacco abuse are related to deficits in self-regulation, an important function of the executive attention network. The evidence for this comes from data that showed an association between several of the core brain areas that underlie self-regulation (e.g., the anterior cingulate and its connections to the striatum) and substance addictions (Goldstein & Volkow, 2011). These same brain areas have also been associated with behavioral compulsions such as gambling and excessive use of the Internet (Hong et al., 2013; Thomsen et al., 2013).

Could the increased skill in task switching that follows from practice or training with computer games or from other forms of attention training lead to greater pleasure in shifting from task to task and hence to an excessive reliance on multitasking? Do people who engage in multitasking come to prefer this strategy rather than doing one thing at a time? There is a paucity of direct evidence on this important point, but several lines of brain research suggest the answer might be affirmative. For example, when one has practiced a difficult task sufficiently to reduce its brain activation by tuning neurons and increasing connectivity, the effort needed to perform the task is reduced. At that point, the act of performing the task can lead to a pleasurable *optimal flow state* in which the person's skills are matched to the challenge of the activity and attention and action seem to flow effortlessly (Bruya, 2010). The flow state refers to the holistic experience that people feel when they are totally absorbed in an activity and lose a sense of time, when the focus of their awareness is narrowed, they become less self-conscious, and feel in control of their environment (Csikzentmihalyi, 1990). The concept has been used to explain a range of activities including information-seeking experiences on-line (Pace, 2007) and by extension, media multitasking. If this is the case, the choice of multitasking may lead to a preference for work or learning environments that require a great deal of task switching rather than those supporting single tasks that require focused attention. However, as with any dependency or addiction, the data on multitasking indicate that personal and temperamental characteristics such as high sensation seeking are important considerations that may put heavy multitaskers at additional risk for acquiring a dependence on task switching activities. Although people may feel overwhelmed by a need to check e-mail or search for new information on the Internet, the same evidence that we have used to support adult brain plasticity argues that it is possible to reduce dependence by allowing a period of recovery from high multitasking activity.

Brain states and addiction

Many forms of addiction appear to show reduced self-regulation due to under-activation of the anterior cingulate and the adjacent mid-frontal cortex and their connections to the striatum (Hong et al., 2013; Thomsen et al., 2013; Volkow & Bailer, 2013). There is good evidence that meditation training can strengthen these very neural pathways and can ameliorate negative outcomes resulting from deficits in self-regulation (Tang et al, 2007, 2009; Tang, Rothbart & Posner, 2012). Reasoning from this common anatomy, it is possible that certain forms of addictive behavior might be reduced or even eliminated by the inclusion of meditation exercises that strengthen self-regulation in their therapeutic programs. For example, addiction to tobacco and the craving for tobacco are known to involve the anterior cingulate, insula, and striatal pathways (Hayashi et al., 2013; Zhang et al., 2011). Tang, Tang, and Posner (2013) showed that strengthening these pathways reduced both the craving for, and use of tobacco products. They recruited a group of participants that included both non-smokers and smokers without any particular intention to quit, for a training program to reduce stress and improve performance. Participants were randomly assigned to a meditation-training group using IBMT or to a general relaxation-training group. Smoking cessation or resisting tobacco cravings were not a part of either program. Following two weeks of training, there was a 60% reduction in the use of tobacco products and a reduction in reported tobacco craving for the IBMT group, but no reduction in either measure for the relaxation training controls. Although the IBMT training focused on improving self-control, that may have improved the capacity to deal with the tobacco craving and smoking behavior. Whether or not participants were actually aware of their reduced tobacco use did not seem to be related to their reduced smoking. Indeed it is quite possible that the desire to quit, for example, by trying not to think about the act of smoking might enhance the craving, just as trying not to think about something often brings that very thing to mind (Wegner, 1989).

Before training, smokers compared to nonsmokers had reduced activity in the anterior cingulate, left lateral prefrontal cortex, and other areas indicative of impaired self-regulation. Resting-state brain scans showed that after IBMT training, smokers showed increased activity in the anterior cingulate and prefrontal cortex, key brain areas related to self-control and addiction, as measured by fractional anisotropy (FA). There was no change in activity for the relaxation-training group. Given that the anatomical overlap between behavioral addiction to gambling or to tobacco and other substances, or to problematic Internet use is substantial, the method of changing brain states through mindfulness meditation may be an important tool in reducing dependence on various forms of compulsive behavior including media multitasking. This is a topic for future research.

Summary and concluding comments

The role of attention and self-regulation in multitasking has been the principal focus of the literature reviewed in this paper. The attention networks of the brain underlie the ability to switch efficiently between tasks and to focus and resist distraction as appropriate, critical skills for multitasking. In adults, these skills rely primarily on the executive attention network including the anterior cingulate, anterior insula, and striatum. The efficient operation of the network depends on the neural computations in these areas and on the connectivity among them. For young children, and when external information is particularly important to older children and adults, the orienting network also plays an important role in performing both single and multiple tasks. However, it is also clear that effective multitasking can be extremely difficult or impossible if the two tasks require the resources of the executive attention network at the same time.

We have also traced the development of orienting and executive attention and discussed the role of these processes in self-regulation and the ability to keep higher-order goals in mind, even when they conflict with current behavior. The evidence from behavioral and neuroimaging studies indicates that the orienting network regulates attention during infancy and early childhood and that only after about age three years does the executive attention system begin to dominate the control and regulation of thought, emotion, and behavior. Both genetic and environmental (e.g., parenting, culture) factors play a role in this shift from orienting to executive control and a failure of the transition to occur can contribute to certain childhood pathologies (e.g., ADHD) that depend on the executive attention network. Further developments in the executive attention network will continue gradually over the early school years, indicating that young children will find multitasking especially challenging. Although for most people the efficiency of executive attention develops significantly between infancy and childhood, there are individual differences in the efficiency with which they operate.

However, there is also evidence from research on neural plasticity that both older children and adults can improve their executive attention and self-regulation through training. These training procedures are varied but have been of two general types. First, attention network training has shown that it is possible to improve network efficiency by practice-oriented exercises that affect the ability to resolve conflict. These exercises provide direct practice on tasks and skills that require the executive attention network (e.g., computer games; working memory). It is also possible to induce training effects through practice with action video games. Although action video games improve orienting network functions rather dramatically, their influence on the executive attention network seems to be more limited, although significant improvements in task switching have been documented.

Neuroimaging studies show that the effects of training on executive attention are evident in the tuning of the brain areas in the network involved and also by improved connectivity between areas through expansion of axons and their myelination. Interestingly, those individuals who choose to immerse themselves in media multitasking do not appear to be particularly good at task switch or attention tasks even when they are confident that they can perform these tasks well (Ophir et al., 2009). This may be because high levels of sensation seeking that co-occur with multitasking lead them to seek out complex environments that diminish the ability to avoid distractions and sustain high-level goals. However, training studies are needed to explore whether those high or low in sensation seeking have similar or different influences from training. Sensation seeking has been related to particular genetic variations that also influence executive attention.

In the second type of training, called attention state training, techniques that can induce a change in brain state are used. These include meditation, hypnosis, and physical exercise. This training is assumed to target a wider range of brain areas and involves the autonomic nervous system as well as the central nervous system. The training method has been shown to improve connectivity between the anterior cingulate and striatum, a pathway that is often deficient when self-regulation is poor; as in behavioral and substance addictions. Direct studies of tobacco addiction by meditation training have shown reduction in craving and smoking behavior after two weeks.

However, even if multitasking can lead to some performance benefits through training, there is still a concern that adolescents and young adults who are the biggest users of media multitasking and the Internet can become dependent on the rapid change of pace that these formats provide, and might then be unable to carry out more sustained goals. Should this prove to be a significant mental health problem, the method of changing brain states through mindfulness meditation offers the possibility of improving possible dependence on various forms of multitasking. Thus, the findings from attention and brain state training studies provide an important perspective for future research on the development of individuals' choices of multitasking activity and the influence of multitasking on brain activity and behavior.

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References

Allen M, Dietz M, Blair KS, van Beek M, Rees G, Vestergaard-Paulsen P, Lutz A, Roepstorff A. Cognitive-affective neural plasticity following active-controlled mindfulness intervention. Journal of Neuroscience. 2012; 32:15601–15610. [PubMed: 23115195]

Baddeley, AD. Working memory, thought and action. Oxford: Oxford University Press; 2007.

Bailey K, West R, Anderson CA. A negative association between video game performance and proactive cognitive control. Psychophysiology. 2010; 47:34–42. [PubMed: 19818048]

Baldwin DA. Infants' contribution to the achievement of joint reference. Child Development. 1991; 62:875–890. [PubMed: 1756664]

Bavelier D, Achtman RL, Mani M, Focker J. Neural basis of selective attention in action video games. Vision Research. 2012; 61:132–143. [PubMed: 21864560]

Bavelier D, Green CS, Pouget A, Schrater P. Brain plasticity through the life span: Learning to learn and action video games. Annual Review of Neuroscience. 2012; 35:391–416.

Belsky J, Pluess M. Beyond diathesis stress: Differential susceptibility to environmental stress. Psychological Bulletin. 2009; 135:895–908.

Berger A, Tzur G, Posner MI. Infant brains detect arithmetic errors. Proceedings of the National Academy of Sciences USA. 2006; 103:12649–12653.

Block JJ. Issues for DSM-V: Internet addiction. American Journal of Psychiatry. 2008; 165:306–307. [PubMed: 18316427]

Bruya, B. Effortless attention. Cambridge MA: MIT Press; 2010.

Buschkuehl M, Jaeggi SM, Jonides J. Neuronal effects following working memory training. Developmental Cognitive Neuroscience. 2012; 15 (Suppl 1):S167–79. [PubMed: 22682905]

Bush G, Luu P, Posner MI. Cognitive and emotional influences in the anterior cingulate cortex. Trends in Cognitive Science. 2000; 4:215–222.

Cain MS, Landau AN, Shimamura AP. Action video game experience reduces the cost of switching tasks. Attention Perception & Psychophysics. 2012; 74:641–647.

Carbonell, JG. Subjective understanding: Computer models of belief systems. Ann Arbor, MI: UMI Research Press; 1981.

Casey BJ, Somerville LH, Gotlib IH, Ayduk O, Franklin NT, Askren MK, Jonides J, Berman MG, Wilson NL, Teslovich T, Glover G, Zayas V, Mischel W, Shoda Y. Behavioral and neural correlates of delay of gratification 40 years later. Proceedings of the National Academy of Sciences USA. 2011; 108:14998–15003.

Checa P, Castellanos MV, Abundis-Gutierrez A, Rueda MR. Development of neural mechanisms of conflict and error processing during childhood: implications for self-regulation. Frontiers in Psychology. 201410.3389/fpsyg.2014.00326

Chiappe D, Conger M, Liao J, Caldwell JL, Vu K-PL. Improving multitasking ability through action videogames. Applied Ergonomics. 2013; 44:278–284. [PubMed: 22981314]

Clohessy AB, Posner MI, Rothbart MK. Development of the functional visual field. Acta Psychologica. 2001; 106:51–68. [PubMed: 11256339]

Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nature Reviews Neuroscience. 2002; 3:201–215.

Courage ML, Bakhtiar A, Fitzpatrick C, Kenny S, Brandeau K. Growing up Multitasking: The Costs and Benefits for Cognitive Development. Developmental Review. 2015 (this issue).

Csikszentmihalyi, M. Flow. New York: Harper & Row; 1990.

Deco G, et al. Emerging concepts for the dynamical organization of resting-state activity in the brain. Nature Reviews Neuroscience. 2011; 12:43–56.

Dehaene S, Posner MI, Tucker DM. Localization of a neural system for error detection and compensation. Psychological Science. 1994; 5:303–305.

Diamond A. Development of the ability to use recall to guide action as indicated by infants' performance on A-not-B. Child Development. 1985; 56:868–883. [PubMed: 4042750]

Diamond A, Barnett WS, Thomas J, Monroe S. Preschool program improves cognitive control. Science. 2007; 318:1387–1388. [PubMed: 18048670]

Diamond A, Lee K. Interventions shown to aid executive function development in children 4 to 12 years old. Science. 2012; 333:959–64. [PubMed: 21852486]

Dien J, Spencer KM, Donchin E. Localization of the event-related potential novelty response as defined by principal components analysis. Cognitive Brain Research. 2003; 17:637–650. [PubMed: 14561451]

Donchin E. Surprise! … Surprise? Psychophysiology. 1981; 18:493–515. [PubMed: 7280146]

Dosenbach NUF, Fair DA, Miezin FM, Cohen AL, Wenger KKR, Dosenbach AT, Fox MD, Snyder AZ, Vincent JL, Raichle ME, Schlaggar BL, Petersen SE. Distinct brain networks for adaptive and stable task control in humans. Proceedings of the National Academy of Sciences USA. 2007; 104:1073–1978.

Fair DA, Cohen AL, Power JD, Dosenbach NUF, Church JA, Miezin FM, Schlaggar BL, Petersen SE. Functional brain networks develop from a "local to distributed" organization. Public Library of Science Computational Biology. 2009; 5:1–13.

Fan J, Gu X, Guise KG, Liu X, Fossella J, Wang H, Posner MI. Testing the behavior interaction and integration of attentional neworks. Brain and Cog. 2009; 70:209–220.

Fan J, McCandliss BD, Sommer T, Raz M, Posner MI. Testing the efficiency and independence of attentional networks. Journal of Cognitive Neuroscience. 2002; 3:340–347. [PubMed: 11970796]

Farooqui AA, Mitchell DM, Thompson R, Duncan J. Hierarchical organization of cognition reflected in distributed fronto-parietal activity. Journal of Neuroscience. 2012; 32:17373–17381. [PubMed: 23197728]

Fjell AM, Walhovd K, Brown T, Kuperman J, Chung Y, Hagler D, et al. Multi-modal imaging of the self-regulating brain. Proceedings of the National Academy of Sciences USA. 2012; 109:19620–19625.

Gao W, Gilmore JH, Shen D, Smith JK, Zhu H, Lin W. The synchronization within and interaction between the default and dorsal attention networks in early infancy. Cerebral Cortex. 2013; 23:594–603. [PubMed: 22368080]

Gao W, Zhu H, Giovanello KS, Smith JK, Shen D, Gilmore JH, Lin W. Evidence on the emergence of the brain's default network from 2-week-old to 2-year-old healthy pediatric subjects. Proceedings of the National Academy of Sciences USA. 2009; 106:6790–6795.

Gerardi-Caulton G. Sensitivity to spatial conflict and the development of self-regulation in children 24–36 months of age. Developmental Science, fjell. 2000:397–404.

Goldstein RZ, Volkow ND. Drug addiction and its underlying neurological basis: Neuroimaging evidence for the involvement of the frontal cortex. American Journal of Psychiatry. 2002; 159:1642–1652. [PubMed: 12359667]

Green AE, Munafo MR, DeYoung CG, Fossella JA, Fan J, Gray JR. Using genetic data in cognitive neuroscience: from growing pains to genuine insights. Nature Reviews Neuroscience. 2008; 9:710–20.

Green CS, Bavelier D. Action video games modify visual selective attention. Nature. 2003; 423:534–537. [PubMed: 12774121]

Green CS, Sugarman MA, Medford K, Klobusicky E, Bavelier D. The effect of action video game experience on task-switching. Computers in Human Behavior. 2012; 28:984–994. [PubMed: 22393270]

Gusnard DA, Raichle ME. Searching for a baseline: functional imaging and the resting human brain. Nature Reviews Neuroscience. 2001; 2:685–689.

Haith MM, Hazan C, Goodman GS. Expectations and anticipations of dynamic visual events by 3.5-month-old babies. Child Development. 1988; 59:467–469. [PubMed: 3359865]

Harman C, Rothbart MK, Posner MI. Distress and attention interactions in early infancy. Motivation and Emotion. 1997; 21:27–43.

Hayashi T, Ko JH, Strafella AP, Dagher A. Dorsolateral prefrontal and orbitofrontal cortex interactions during self-control of cigarette craving. Proceedings of the National Academy of Sciences USA. 2013; 110:4422–4427.

Hebb, DO. Organization of Behavior. Wiley; New York: 1949.

Hofman W, Schmeichel BJ, Baddeley AD. Executive function and self-regulation. Trends in Cognitive Science. 2012; 16:174–180.

Hölzel BK, Ott U, Hempel H, Hackl A, Wolf K, Stark R, Vaitl D. Differential engagement of anterior cingulate and adjacent medial frontal cortex in adept meditators and non-meditators. Neuroscience Letters. 2007; 421:16–21. [PubMed: 17548160]

Hong SB, Kim J-W, Choi E-J, Kim H-H, Suh J-E, Kim C-D, Klauser P, Whittle S, Pantelis C, Yi SH. Reduced orbitofrontal cortical thickness in male adolescents with internet addiction. Behavioral and Brain Function. 2013; 9:11.

Isaacowitz DM. Mood regulation in real time: Age differences in the role of looking. Current Direction in Psychological Science. 2012; 21:237–242.

Jaeggi SM, Buschkuehl M, Jonides J, Perrig WJ. Improving fluid intelligence with training on working memory. Proceedings National Academy Sciences USA. 2008; 105:6829–683.

Jeong S, Fishbein M. Predictors of multi-media use and multitasking with media: Media factors and audience. Media Psychology. 2007; 10:364–384.

Jones LB, Rothbart MK, Posner MI. Development of executive attention in preschool children. Developmental Science. 2003; 6:498–504.

Jost KK, Mayr U, Rosler F. Is task switching nothing but cue priming? Evidence for ERPs. Cognitive, Affective, & Behavioral Neuroscience. 2008; 8:74–84.

Klingberg T. Training and plasticity of working memory. Trends in Cognitive Science. 2010; 14:317–324.

Ko CH, Yen JY, Yen CF, Chen CS, Chen CC. The association between internet addiction and psychiatric disorder: A review of the literature. European Psychiatry. 2010; 27:1–8. [PubMed: 22153731]

Kochanska G, Murray KT, Harlan ET. Effortful control in early childhood: Continuity and change, antecedents and implications for social development. Developmental Psychology. 2000; 36:220–232. [PubMed: 10749079]

Kramer AF, Erickson KI. Capitalizing on cortical plasticity: Influence of physical activity on cognition and brain function. Trends in Cognitive Science. 2007; 11:342–348.

Kuhl PK. Brain mechanisms in early language acquisition. Neuron. 2010; 67:713–727. [PubMed: 20826304]

Leiberg S, Klimecki O, Singer T. Short-term compassion training increases prosocial behavior in a newly developed prosocial game. Public Library of Science One. 2011; 6:e17798. [PubMed: 21408020]

Lewkowicz DJ, Hansen-Taft AM. Infants deploy selective attention to the mouth of a talking face when learning speech. Proceedings of the National Academy of Sciences USA. 2012; 109:1431–1436.

Lin L. Breadth-biased versus focused cognitive control in media multitasking. Proceedings of the National Academy of Science USA. 2009; 106:15521–15522.

Luria, AR. The working brain. New York: Basic Books; 1973.

Mantyla T. Gender differences in multitasking reflect spatial ability. Psychological Science. 2013; 24:514–520. [PubMed: 23462757]

Markett SA, Montag C, Reuter M. The association between dopamine DRD2 polymorphisms and working memory capacity is modulated by a functional polymorphism on the nicotinic receptor gene CHRNA4. Journal of Cognitive Neuroscience. 2010; 22:1944–1954. [PubMed: 19803686]

Miller AJ, Jaroszewski AC, Chamarthi H, Pizzagalli DA. Behavioral and electrophysiological correlates of training-induced cognitive control improvements. Neuroimage. 2012; 63:742–753. [PubMed: 22836178]

Minear M, Brasher M, McCurdy M, Lewis J, Younggren A. Working memory, fluid intelligence, and impulsiveness in heavy media multitaskers. Psychonomic Bulletin & Review. 2013; 20:1274–1281. [PubMed: 23722949]

Mishra J, Zinni M, Bavelier D, Hillyard SA. Neural basis of superior performance of action videogame players in an attention-demanding task. Journal of Neuroscience. 2011; 31:992–998. [PubMed: 21248123]

Moffitt TE, Arseneault L, Belsky D, Dickson N, Hancox RJ, Harrington HL, Houts R, Poulton R, Roberts BW, Ross S, Sears MR, Thomson WM, Caspi A. A gradient of childhood self-control predicts health, wealth and public safety. Proceedings of the National Academy of Sciences USA. 2011; 108:72693–72698.

Monsell S. Task switching. Trends in Cognitive Science. 2002; 7:137–140.

Moruzzi G, Magoun HW. Brain stem reticular formation and activation of the EEG. EEG & Clinical Neurophysiology. 1949; 1:455–473.

NICHD Early Child Care Research Network. ERIC Document Reproduction Service No. ED3530870. 1993. The NICHD Study of Early Child Care: A comprehensive longitudinal study of young children’s lives.

Olesen PJ, Westerberg H, Klingberg T. Increased prefrontal and parietal activity after training of working memory. Nature Neuroscience. 2004; 7:75–79.

Ophir E, Nass C, Wagner AD. Cognitive control in media multitaskers. Proceedings of the National Academy of Science USA. 2009; 106:15583–15587.

Pace S. Play and flow: Implications for on-line learning. Studies in Learning, Evaluation, Innovation, and Development. 2007; 4:67–78.

Petersen SE, Posner MI. The attention system of the human brain: 20 years after. Annual Review of Neuroscience. 2012; 35:71–89.

Posner, MI. Attention in a social world. New York: Oxford University Press; 2012.

Posner, MI.; Rothbart, MK. Educating the human brain. Washington DC: American Psychological Association; 2007a.

Posner MI, Rothbart MK. Research on attention networks as a model for the integration of psychological science. Annual Review of Psychology. 2007b; 58:1–23.

Posner MI, Rothbart MK, Sheese BE, Voelker P. Control networks and neuromodulators of early development. Developmental Psychology. 2012; 48:827–835. [PubMed: 21942663]

Powers KL, Brooks PJ, Aldrich NJ, Palladion MA, Alfieri L. Effects of video-game play on information processing: a meta-analytic investigation Psychonomic Bulletin and Review. 2013; 20:1055–1079.

Pumprla J, Howorka K, Groves D, Chester M, Nolan J. Functional assessment of heart rate variability: Physiological basis and practical applications. International Journal of Cardiology. 2002; 84:1–14. [PubMed: 12104056]

Raichle ME. A paradigm shift in functional imaging. Journal of Neuroscience. 2009; 29:12729–12734. [PubMed: 19828783]

Raichle ME. Two views of brain function. Trends in Cognitive Sciences. 2010; 14:180–190. [PubMed: 20206576]

Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, Shulman GL. A default mode of brain function. Proceedings of the National Academy of Sciences USA. 2001; 98:676–682.

Raz A, Buhle J. Typologies of attentional networks. Nature Reviews Neuroscience. 2006; 7:367–79.

Reuter M, Ott U, Vaitl D, Hennig J. Impaired executive control is associated with a variation in the promoter region of the tryptophan hydroxylase 2 gene. Journal of Cognitive Neuroscience. 2007; 19:401–408. [PubMed: 17335389]

Rothbart, MK. Becoming who we are: Temperament, personality and Development. New York: Guilford Press; 2011.

Rothbart MK, Ahadi SA, Hersey KL, Fisher P. Investigations of temperament at three to seven years: The Child Behavior Questionnaire. Child Development. 2001; 72:1394–1408. [PubMed: 11699677]

Rothbart MK, Ellis LK, Rueda MR, Posner MI. Developing mechanisms of effortful temperamental control. Journal of Personality. 2003; 71:1113–1143. [PubMed: 14633060]

Rothbart MK, Sheese BE, Rueda MR, Posner MI. Developing mechanisms of self-regulation in early life. Emotion Review. 2011; 3:207–213. [PubMed: 21892360]

Rothbart, MK.; Ziaie, H.; O'Boyle, CG. Self-regulation and emotion in infancy. In: Eisenberg, N.; Fabes, RA., editors. Emotion and its regulation in early development: New directions for child development, No. 55: The Jossey-Bass education series. San Francisco: Jossey-Bass Publishers; 1992. p. 7-23.

Rueda, MR. Effortful Control. In: Zentner, M.; Shiner, RL., editors. Handbook of Temperament. New York: Guilford Press; 2012. p. 145-167.

Rueda MR, Checa P, Combita LM. Enhanced efficiency of the executive attention network after training in preschool children: immediate and after two month effects. Developmental Cognitive Neuroscience. 2012; 2(Suppl 1):S192–S204. [PubMed: 22682908]

Rueda MR, Fan J, Halparin J, Gruber D, Lercari LP, McCandliss BD, Posner MI. Development of attention during childhood Neuropsychologia. 2004; 42:1029–1040.

Rueda MR, Rothbart MK, McCandliss BD, Saccomanno L, Posner MI. Training, maturation and genetic influences on the development of executive attention. Procedings of the National Academy of Sciences USA. 2005; 102:14931–14936.

Ruff, HA.; Rothbart, MK. Attention in early development. New York: Oxford University Press; 1996.

Rushworth MFS, Hadland KA, Gaffan D, Passingham RD. The effect of cingulate cortex lesions on task switching and working memory. Journal of Cognitive Neuroscience. 2003; 15:338–353. [PubMed: 12729487]

Rushworth MFS, Passingham RS, Nobre AC. Components of switching intentional set. Journal of Cognitive Neuroscience. 2002; 14:1139–1150. [PubMed: 12495521]

Sanbomnatsu DM, Strayer DL, Medieros-Ward N, Watson JM. Who multi-tasks and why? Multi-tasking ability, perceived multi-tasking ability, impulsivity, and sensation seeking. PLoS One. 2013; 8(1):e54402.10.1371/journal.pone.0054402 [PubMed: 23372720]

Sheese BE, Rothbart MK, Voelker P, Posner MI. The dopamine receptor D4 gene 7 repeat allele interacts with parenting quality to predict effortful control in four-year-old children. Child Development Research. 2012; 12:Article ID 863242.

Sheese BE, Rothbart MK, Posner MI, White LK, Fraundorf SH. Executive attention and self-regulation in infancy. Infant Behavior and Development. 2008; 31:501–510. [PubMed: 18406466]

Sheese BE, Voelker PM, Rothbart MK, Posner MI. Parenting quality interacts with genetic variation in dopamine receptor DRD4 to influence temperament in early childhood. Development & Psychopathology. 2007; 19:1039–1046. [PubMed: 17931433]

Sheth SA, Mian MK, Patel SR, Asaad WF, Williams ZM, Dougherty DD, Bush G, Eskander EN. Human dorsal anterior cingulate cortex neurons mediate ongoing behavioural adapation. Nature. 2012; 488:218. [PubMed: 22722841]

Shulman GL, Astafiev SV, Franke D, Pope DLW, Snyder AZ, McAvoy MP, Corbetta M. Interaction of stimulus-driven reorienting and expectation in ventral and dorsal frontoparietal and basal ganglia-cortical networks. Journal of Neuroscience. 2009; 29:4392–4407. [PubMed: 19357267]

Smith HJ, Sheikh HI, Dyson MW, Olino TM, Laptook RS, Durbin CE, Hayden EP, Singh SM, Klein DN. Parenting and child *DRD4* genotype interact to predict children's early emerging effortful control. Child Development. 2012; 83:1932–1944. [PubMed: 22862680]

Spector, T. Identically different: Why you can change your genes. London: Orion Publishing; 2012.

Sridharan D, Levitin DJ, Menon V. A critical role of the right fronto-insular cortex in switching between central-executive and default mode networks. Proceedings of the National Academy of Science USA. 2008; 105:12569–12574.

Strobach T, Frensch PA, Schubert T. Video game practice optimizes executive control skills in dual-task and task switching situations. Acta Psychologica. 2012; 140:13–24. [PubMed: 22426427]

Tang YY, Ma Y, Fan Y, Feng H, Wang J, Feng S, Lu Q, Hu B, Lin Y, Li J, Zhang Y, Wang Y, Zhou L, Fan M. Central and autonomic nervous system interaction is altered by short-term meditation. Proceedings of the National Academy of Sciences, USA. 2009; 106:8865–8867.

Tang YY, Ma Y, Wang J, Fan Y, Feng S, Lu Q, Yu Q, Sui D, Rothbart MK, Fan M, Posner MI. Short-term meditation training improves attention and self-regulation. Proceedings of the National Academy of Sciences USA. 2007; 104:17152–17156.

Tang YT, Posner MI. Training brain networks and states. Trends in Cognitive Sciences. 2014; 18:345–350. [PubMed: 24816329]

Tang YY, Rothbart MK, Posner MI. Neural correlates of establishing, maintaining and switching brain states. Trends in Cognitive Science. 2012; 16:330–337.

Tang YY, Lu Q, Geng X, Stein EA, Yang Y, Posner MI. Short-term mental training induces white-matter changes in the anterior cingulate. Proceedings of the National Academy of Sciences USA. 2010; 107:16649–16652.

Tang YY, Tang R, Posner MI. Brief meditation traininginduces spontaneous smoking reduction. Proceedings of the National Academy of Sciences USA. 2013; 110:13971–13975.

Tang YY, Yang L, Leve L, Harold G. Improving executive function and its neurobiological mechanisms through a mindfulness-based intervention: Advances within the field of developmental neuroscience. Child Development Perspectives. 2012; 6:361–366. [PubMed: 25419230]

Taylor PCJ, Nobre AC, Rushworth MFS. Subsequent changes in top down control exerted by medial frontal cortex during conflict and action selection: a combined transcranial magnetic stimulation and electroencephalography study. Journal of Neuroscience. 2007; 27:11343–11353. [PubMed: 17942729]

Thomsen KR, Joensson M, Lou HC, Muller A, Gross J, Kringelbach MI, Changeux JP. Altered paralimbic interaction in behavioral addiction. Proceedings of the National Academy of Sciences USA. 2013; 110:4744–4749.

van Schouwenburg MR, O’Shea J, Mars RB, Rushworth MFS, Cools R. Controlling human striatal cognitive function via the frontal cortex. Journal of Neuroscience. 2012; 32:5631–37. [PubMed: 22514324]

Volkow, N.; Baler, R. Addiction: A disease of self-control. In: Battro, AM.; Dehaene, S.; Singer, WJ., editors. Neurosciences and the human person: New perspectives on human activities. Vatican City: Vatican Press; 2013.

Vygotsky, LS. Thought and language. Cambridge, MA: MIT Press; 1934.

Wallace RK. Physiological effects of transcendental meditation. Science. 1970; 167:1751–1754. [PubMed: 5416544]

Wegner, DM. White bears and other unwanted thoughts: Suppression, obsession, and the psychology of mental control. New York: Viking/Penguin. Wegner; 1989.

Werker JF, Tees RC. Influences on infant speech processing: Toward a new synthesis. Annual Review of Psychology. 1999; 50:509–35.

Westerberg H, Klingberg T. Changes in cortical activity after training in working memory - a single-subject analysis. Physiology & Behavior. 2007; 92:186–192. [PubMed: 17597168]

Wynn K. Addition and subtraction by human infants. Nature. 1992; 358:749–750. [PubMed: 1508269]

Young, KS.; Cristiano, ND. Internet addiction: A handbook and guide to evaluation and treatment. New York: John Wiley & Sons; 2010.

Zeidan F, Johnson SK, Diamond BJ, David Z, Goolkasian P. Mindfulness meditation improves cognition: evidence of brief mental training. Consciousness and Cognition. 2010; 19:597–605. [PubMed: 20363650]

Zhang XC, Salmeron BJ, Ross TJ, Geng XJ, Yang YH, Stein EA. Factors underlying prefrontal and insula structural alterations in smokers. Neuroimage. 2011; 55:42–48. [PubMed: 20699124]

Highlights

This article connect work in mulititasking with attentional networks related to orienting, alerting and executive control. It reviews efforts to improve these networks by training and proposes methods that might improve multitasking and reduce addiction.

Table 1

Brain Attention Networks Anatomy, Dominant Modulators and Genetic Alleles

NETWORK	**MODULATOR**	**GENES**
ALERTING	NOREPINEPHRINE	ADRA2A
LOCUS COERULEUS		NET
RIGHT FRONTAL CORTEX		
RIGHTPARIETAL COREX		
ORIENTING	ACETYCHOLINE	CHRNA4
FRONTAL EYE FIELDS		APOE
SUPERIOR PARIETAL LOBE		
TEMPORAL PARIETAL JUNCTION		
SUPERIOR COLLICULUS		
PULVINAR		
EXECUTIVE	DOPAMINE	DRD4, DAT1, COMT
ANTERIOR CINGULATE		MAOA, DBH
ANTERIOR INSUA	SEROTONIN	TPH2, 5HTT
FRONAL CORTEX		
STRIATUM		

This table was adapted from Green et al. (2008)