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The Development of Executive Attention: Contributions to the Emergence of Self-Regulation

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Over the past decade, developmental studies have established connections between executive attention, as studied in neurocognitive models, and effortful control, a temperament system supporting the emergence of self-regulation. Functions associated with the executive attention network overlap with the more general domain of executive function in childhood, which also includes working memory, planning, switching, and inhibitory control (Welch, 2001). Cognitive tasks used with adults to study executive attention can be adapted to children and used with questionnaires to trace the role of attention and effortful control in the development of self-regulation. In this article we focus on the monitoring and control functions of attention and discuss its contributions to self-regulation from cognitive, temperamental, and biological perspectives.

> Self-Regulation refers to the many processes by which the human psyche exercises control over its functions, states, and inner processes. It is an important key to how the self is put together. Most broadly, it is essential for transforming the inner animal nature into a civilized human being. (Vohs & Baumeister, 2004, p. 1)

The ability to control one's behavior plays an important role in the development of personality and the socialization of the child. Self-regulation has been related to

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emotionality, delay of gratification, compliance, moral development, social competence, empathy, adjustment, and cognitive and academic performance (Eisenberg, Smith, Sadovsky, & Spinrad, 2004). In addition, self-regulation is thought to be the key mediator between genetic predispositions, early experience, and adult functioning (Fonagy & Target, 2002).

Over the past decade, studies have attempted to integrate the study of attention and self-regulation (Posner & Rothbart, 1992, 1998). During the 1st year of life, attentional orienting appears to act as a distress regulator (Harman, Rothbart, & Posner, 1997). In successive months, infants experience a transition from a more reactive or stimulus-driven form of attentional selection toward more controlled attention (Rothbart, Posner, & Boylan, 1990). This transition supports the voluntary control of action needed to regulate one's behavior (Posner & Rothbart, 1998). Although attention and self-regulation have been studied within two very different research traditions, we have made an effort to integrate these bodies of literature by considering hypotheses about the specific neural mechanisms involved in self-regulation and their connection to executive attention and effortful control (Rueda, Posner, & Rothbart, 2004). In this article, we analyze the cognitive, temperamental, and biological systems supporting attentional control and its contributions to the emergence of self-regulation. In addition, we report our recent efforts to trace and foster the development of this aspect of attention in young children.

EFFORTFUL CONTROL

Links between attention and self-regulation have been found in temperament research. In these studies, individual differences are commonly measured using temperament or personality questionnaires. Effortful control consistently emerges from factorial analysis of temperament questionnaires, with temperament scales loading on the factor including shifting and focusing attention, inhibitory control, perceptual sensitivity, and low-intensity pleasure. Effortful control allows individuals to regulate their behavior in relation to current and future needs, as in situations that involve coping with immediate punishment or avoiding instant reward in the face of a more rewarding situation in the future.

Rothbart, Ahadi, and Hershey (1994) showed that 6- and 7-year-olds high in effortful control were high in empathy and guilt/shame and low in aggressiveness. Eisenberg and her colleagues found that 4- to 6-year old boys with good attentional control tend to deal with anger by using nonhostile verbal methods rather than overt aggressive methods (Eisenberg, Fabes, Nyman, Bernzweig, & Pinulas, 1994). In line with these data, the work by Kochanska and colleagues over the past decade has shown that effortful control plays an important role in the development of conscience. In studies of temperament and conscience, the early internalization of moral principles appears to be facilitated in fearful preschool-age children, especially when their mothers use gentle discipline (see Kochanska, 1991, 1995, 1997). In addition, internalized control is greater in children who are high in effortful control (Kochanska, Murray, & Harlan, 2000; Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996).

Individual differences in effortful control are also related to aspects of metacognitive knowledge, such as theory of mind (i.e., knowing that people's behavior is guided by their beliefs, desires, and other mental states; Carlson & Moses, 2001). Tasks that require inhibitory control are correlated with performance on theory of mind tasks even when other factors such as age, planning skills, and receptive vocabulary are factored out (Carlson, Moses, & Claxton, 2004).

All these data point to the idea that effortful control serves as the basis for the development from more reactive to more self-regulative behavior. Systems of effortful control may contribute to this development by providing the attentional flexibility required to manage negative affect, consider potential actions in light of moral principles, and coordinate reactions that are under voluntary control (Rothbart & Rueda, 2005).

VOLUNTARY CONTROL OF ACTION

Selecting information and controlling thoughts and actions have been a major function of attention from the earliest theoretical models (Broadbent, 1958; James, 1890). Attentional selection has an important adaptive role in individuals' interactions with the environment. Even simple behaviors (e.g., reaching for a pencil lying on a table among other objects) require selecting the stimulus toward which the action is directed. Orienting attention over a scene and selecting the object or location to attend to is necessary for carrying out desired actions. Likewise, attention can be directed internally to coordinate memories, thoughts, and emotions.

The attentional system exerts its influence by modulating the functioning of systems involved in information processing. Many of the studies of the regulatory aspect of attention involve modulation of sensory systems. Studies using functional magnetic resonance imaging (fMRI) and cellular recording have demonstrated that a number of brain areas such as the superior parietal lobe and temporal parietal junction play a key role in modulating activity within primary and extrastriate visual systems when attentional orienting occurs (Corbetta & Shulman, 2002; Desimone & Duncan, 1995). In addition, other neuroimaging studies have suggested that the regulatory effects of attention apply just as well to brain areas involved in processing the semantics of words, storing information in memory, and generating emotions such as fear and sadness (Posner & Raichle, 1994, 1998).

Attention can be automatically driven by external stimulation or endogenously controlled by the goals and wishes of the individual. Norman and Shallice (1986) developed a cognitive model for distinguishing between automatic and controlled processes. According to their model, psychological-processing systems rely on a number of hierarchically organized schemas of action and thought used for routine actions. These schemas are automatically triggered and contain well-learned responses or sequences of actions. However, a different mode of operation involving the Supervisory Attention System is required when situations call for more carefully elaborated responses. These are situations that involve (a) novelty, (b) error correction or troubleshooting, (c) some degree of danger or difficulty, or (d) overcoming strong habitual responses or tendencies.

Data from multiple domains have supported the existence of three brain networks that contribute to attention (Posner & Dehaene, 1994; Posner & Petersen, 1990). These networks carry out the functions of alerting, orienting, and executive control. Alerting is the most elementary aspect of attention and describes the state of wakefulness and arousal of an organism; orienting is the selection of information from sensory input; and executive control involves the mechanisms for resolving conflict among thoughts, feelings, and responses. The three brain networks have been shown to differ in their functional anatomy, the circuitry of their component operations, and the neurochemical modulators that influence their efficiency (Posner & Fan, in press). Among these networks, executive control is the network involved in the volitional and controlled aspect of the attentional system. Its functions include resolving into appropriate actions the kinds of situations described by Norman and Shallice as requiring cognitive control (Posner & DiGirolamo, 1998).

What are the cognitive mechanisms by which the voluntary control of behavior is achieved, and how is the study of these mechanisms approached in cognitive neuroscience? We address these questions in the next sections.

MECHANISMS OF CONTROL

Conscious Detection

According to Posner and Raichle (1994), the executive attention network serves the function of

> bringing an object into conscious awareness. … [Detection is further defined as] more than the conscious recognition that an object is present. It may also include recognition of the object's identity and the realization that the object fulfills a sought-after goal … . In this sense, detection is the conscious execution of an instruction. (pp. 168–169)

Conscious detection plays a special role in selecting a target stimulus from among alternatives and engages attention in a way that resists interference by other signals. One way to study detection is by presenting target stimuli among distractors. Imaging studies have shown that, independent of the type of target stimulus (color, motion, form, etc.), particular brain areas are specifically activated by detected targets as contrasted to passive viewing of the same type of stimuli (Corbetta & Shulman, 2002).

A type of detection particularly interesting for action monitoring is the detection of erroneous responses. Detecting errors is one of the functions attributed to the Supervisory Attention System in the Norman and Shallice's (1986) model. A behavioral indicator of error detection and correction is the slowing of reaction time immediately following the commission of an error. An electrophysiological component, the error-related negativity (ERN), is also consistently recorded following the participant's detection of an error (Gehring, Gross, Coles, Meyer, & Donchin, 1993). Further, the distribution of the activity associated with the ERN on the scalp has been linked to activity originating in the anterior cingulate cortex (ACC; van Veen & Carter, 2002), a brain region that, as we discuss later, is related to executive attention.

Inhibition

Inhibitory mechanisms have been widely discussed in cognitive psychology as involved in attention, memory, and language processes (Dagenbach & Carr, 1994). In the attentional domain, inhibition has been studied in connection to both the orienting and the executive functions of attention (Fuentes, 2004) and therefore appears to be essential to attentional selection and executive control. The negative priming phenomenon—increased reaction time to stimuli that have been previously ignored—is an example of the influence of inhibitory processes on attentional selection. In a widely accepted interpretation of negative priming, the effect is accounted for by an inhibitory process that acts on the representation of the ignored information, allowing the system to focus on information relevant for current action (Houghton & Tipper, 1994).

Inhibition is also required for withholding responses that, although prompted by current stimulation, might not be appropriate. The most common way to measure response inhibition is by using tasks in which participants respond to one stimulus but are required to inhibit their response when a related stimulus is presented (Go/No-Go tasks). Under Go/No-Go instructions, promptness to respond can be manipulated by varying the proportion of Go trials or by presenting a No-Go signal at varying time intervals after the Go stimulus (the Stop-signal Paradigm). The efficiency of inhibition is measured behaviorally by the number of omissions and false alarms, but it can be also measured using physiological indices, such as muscular preparation or brain activity.

Conflict Resolution

Monitoring and resolving conflict between incompatible responses also requires voluntary and attentive control of action (Posner & DiGirolamo, 1998). Conflict resolution involves selecting a subdominant object or response in the presence of a competing dominant object or response. Cognitive tasks involving conflict have been used extensively to measure the efficiency with which control of action is exerted (Botvinick, Braver, Barch, Carter, & Cohen, 2001).

Conflict can be induced in many ways. A very popular way is the Stroop task. The original form of this task required participants to report the color of ink in which a word was written, when the color word (e. g., *red*) might conflict with the color of ink (e.g., blue). In general, Stroop-like tasks induce conflict by requiring a response to a stimulus that is incongruent with the one suggested by the stimulus. For example, in the Spatial Conflict task (Gerardi-Caulton, 2000), the requirement is to respond to the identity of a stimulus regardless of its spatial compatibility with the matching response key. The Flanker task (Eriksen & Eriksen, 1974), another widely used task for studying executive attention, induces conflict by presenting additional stimulation in the display, suggesting a response incompatible with the correct one. A recent study carried out by Fan, Flombaum, McCandliss, Thomas, and Posner (2003) showed that these three types of tasks (Stroop color, Spatial Conflict, and Flanker task) activate a common set of brain regions (although to different extents) as well as areas unique to each task, suggesting a common underlying process implemented according to the specific requirements of the task.

THE NEURAL SYSTEM FOR ATTENTIONAL CONTROL

Anatomy and Circuitry

Many of the tasks described earlier have been used together with neuroimaging techniques to localize the brain regions related to executive attention. Data from many studies have shown that situations requiring attentional control activate a neural network including the ACC and lateral prefrontal areas (Posner & Fan, in press). Other studies have attempted to dissociate different operations involved in the control of action, identifying brain areas within the executive network responsible for these operations (Casey, Durston, & Fossella, 2001). In fMRI studies, the ACC was found to be involved in the detection and monitoring of conflict, whereas lateral prefrontal areas were shown to be mainly related to processes required to resolve the conflict (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Detection and resolution of conflict have also been anatomically dissociated from selection of the relevant information, which involves areas of the superior parietal cortex and superior frontal gyrus (Casey et al., 2000).

The main node of the executive attention network, the ACC, is part of the limbic system and is strongly connected to structures involved in processing emotions. In a meta-analysis of imaging studies, the dorsal section of the anterior cingulate was found to be activated in cognitive conflict tasks such as variants of the Stroop task (Bush, Luu, & Posner, 2000). An adjacent area of the anterior cingulate was found to be activated by emotional tasks and emotional states. The two divisions also seem to interact, so that when the cognitive division was activated, the affective division tended to be deactivated and vice versa, suggesting the possibility of reciprocal effortful and emotional controls of attention (Bush et al., 2000). Cingulate activity as shown by fMRI was also found to be related to the instruction of regulating sexual arousal induced by watching videos (Beauregard, Levesque, & Bourgouin, 2001). In a different study, cognitive reappraisal of photographs producing negative affect showed a correlation between extent of cingulate activity and the reduction in negative affect (Ochsner, Bunge, Gross, & Gabrieli, 2002). These results show a role for this anatomical structure in regulating limbic activity related to emotion and provide evidence for a role of the cingulate as a part of the network controlling affect.

A number of studies have used the high temporal resolution of event-related potentials (ERPs) to assess the timing of action-monitoring processes with adults. One of the ERP indexes associated with executive control, the N2, is a preresponse negative deflection in the ERP at around 300 msec poststimulus, which appears to be larger (more negative) for trials involving more conflict. The N2 is observed over parietal and frontal leads and has been obtained with both flanker (Kopp, Rist, & Mattler, 1996; van Veen & Carter, 2002) and Go/No-Go tasks (Jackson, Jackson, & Roberts, 1999). In both situations, the N2 has been associated with the withholding of a prepotent, but inappropriate, response. In a recent ERP study with a Flanker task, van Veen and Carter (2002) linked the scalp distribution of activity associated with the N2 to a source of activation originating at the caudal portion of the ACC, supporting a connection between this electrophysiological index and the executive attention network.

Neurochemistry

The ventral tegmental area, a source of dopamine (DA) neurons, strongly projects to the brain areas involved in executive attention. In addition, all types of DA receptors are expressed within the cingulate cortex. DA appears to be an important modulator of performance on tasks that entail executive functions and involve dorsolateral prefrontal cortex (Diamond & Goldman-Rakic, 1989). Some studies have shown evidence of DA modulation of prefrontal function in the rat (Seamas, Floresco, & Phillips, 1998). In addition, administering DA D_1 receptor agonists and antagonists appears to respectively enhance and impair the accuracy level of performance of rats in a task that requires detecting brief visual targets (Granon et al., 2000). In humans, tasks that involve conflict and require inhibition also appear to be more sensitive to DA levels than tasks with a stronger working memory component, although both types of tasks rely on lateral prefrontal structures (Diamond, Briand, Fossella, & Gehlbach, 2004).

Genetics

Links between the anatomy of executive attention and the chemical modulators involved in its functioning have provided a tool for studying the genetic basis of this network. Pioneering studies following this approach have shown attentional processes related to cognitive control to be determined in part by the biological processes expressed through particular dopamine-related genes (Goldberg & Weinberger, 2004).

Recently, Fan, McCandliss, Sommer, Raz, and Posner (2002) developed the Attention Network Test (ANT). This task provides a measure for each of the three anatomically defined attention networks: alerting, orienting, and executive attention. The ANT can be used as a phenotype of the efficiency of the attentional functions. In a small-scale twin study using the ANT, the executive network showed high-enough heritability (0.89) to justify the search for specific genes (Fan, Wu, Fossella, & Posner, 2001). In a second study, DNA from cheek swabs of participants who performed the ANT was used to examine candidate differences in gene polymorphisms related to dopamine. This process showed at least two candidate genes that were related to the executive network to a greater degree than to overall performance as measured by RT and accuracy (Fossella, Posner, Fan, Swanson, & Pfaff, 2002). One of these genes was the dopamine D4 receptor gene, widely reported to be associated with attention deficit hyperactivity disorder (ADHD) and with the personality trait of sensation seeking (Swanson et al., 2000). The other was the Monoamine oxidase A gene, related to both dopamine and norepinepherine. In a third study, Fan, Fossella, Sommer, and Posner (2003) showed that these two genes were also related to differences in brain activation within the anterior cingulate gyrus while performing a conflict task.

The Catechol-O-Methyltransferase (COMT) gene, involved in the degradation of dopamine, has also been related to prefrontal executive processes (Egan et al., 2001). A particular variant of the COMT gene (the Met-Met genotype) results in greater levels of dopamine at the synapse due to a lower degradation rate. Some studies have found the Met-Met COMT gene variant to relate to better performance in the Wisconsin Card Sorting Test (Egan et al., 2001; Joober et al., 2002). Diamond et al. (2004) found that children with the Met-Met variant performed better in a conflict task than age-matched children with different polymorphisms of the COMT gene. It is of interest that this genotype did not differentiate between the groups in another task that relied more on working-memory processes.

NEUROCOGNITIVE DEVELOPMENT OF EXECUTIVE ATTENTION

So far we have discussed temperamental, cognitive, and biological aspects that play a role in the development of self-regulation. Different assessment tools can be used to investigate the development of these aspects. Individual differences in the efficiency with which effortful control is exerted in daily life can be assessed using temperament questionnaires. Laboratory tasks from adult studies that have been adapted to children can be used to isolate specific measures of executive attention. In addition, these cognitive tasks can be used online with techniques for brain function assessment to study the biological processes supporting behavioral maturation. At the Attention and Temperament Laboratory in the University of Oregon, we have followed this approach to trace the development of executive attention.

Developmental studies have stressed the relative lack of executive control in infants (Ruff & Rothbart, 1996). However, a sign of the control of cognitive conflict is found at the end of the 1st year of life. Infants younger than 12 months fail to search for an object hidden in a location when previously trained to reach for the object in a different location. After the 1st year, children develop the ability to inhibit the prepotent response toward the trained location and successfully reach for the object in the new location (Diamond, 1991).

At 2 years of age and older, children are able to perform simple tasks in which their reaction time can be measured. In one study, toddlers were asked to perform a task that induces conflict between the identity and the location of an object (Spatial Conflict task; Gerardi-Caulton, 2000). Between 2 and 4 years of age, children progressed from an almost complete inability to carry out the task to relatively good performance. Although 2-year-old children tended to perseverate on a single response, 3-year-olds performed at high accuracy levels, although, like adults, they responded more slowly and with reduced accuracy to incompatible trials. In this study, performance of children in the Spatial Conflict task was related to temperament as reported by parents. Consistent with a similar study conducted with adults (Derryberry & Reed, 1998) where high performance was associated with self-reported attentional control, and low trait anxiety, children who performed well were also described by their parents as more skilled at attentional shifting and focusing, less impulsive, and less prone to frustration reactions. These findings are also consistent with the idea that effortful attention, as measured through questionnaire or laboratory methods, may help individuals constrain negative forms of emotion.

The Visual Sequence Learning (VSL) task can be used to assess implicit and attentional forms of learning in children as young as a few months. In the VSL task, a series of cartoons are presented on three different computer monitors in a predictable sequence. In unambiguous sequences, each location is followed by one and only one subsequent location (e.g., 123123 … , with numbers referring to the monitor in which the stimulus appears). Ambiguous associations refer to sequences where a location is followed by one of two or more different locations, the particular location depending on its place within the sequence (e.g., 121312 …). Learning of ambiguous sequences requires the monitoring of context and, in adult studies, has been shown to depend on lateral prefrontal cortex (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). Previous studies showed that ambiguous associations within sequences of events are not acquired at above-chance levels until about 2 years of age (Clohessy, Posner, & Rothbart, 2001).

We recently conducted a study using the VSL task to further explore the relation between cognitive and temperamental measures of executive control in 2- to 3-year-old children (Rothbart, Ellis, Rueda, & Posner, 2003). In this study, we also used a touch screen version of the Spatial Conflict task and asked the parents to complete the Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001). Children were divided into three groups according to their age: 24–25 months, 30–31 months, and 36–37 months. In consonance with previous data, children in all three groups were able to anticipate the correct locations above chance in ambiguous sequences of the VSL task, therefore demonstrating learning of this type of sequence. In addition, we found a great increase in the ability to perform the Spatial Conflict task between the 2- and 3-year-old groups (see upper part of Table 1). At 30 months, when toddlers were able to perform the Spatial Conflict task more successfully, we found that performance on this task was significantly related to the toddlers' ability to learn ambiguous associations in the VSL paradigm. In addition, in two of the groups, interference in the Spatial Conflict task correlated negatively with temperamental effortful control. For the youngest group, effortful control was also related to the percentage of completed trials, and children in the group that did not complete the task were significantly lower in effortful control and higher in negative affect than those completing sufficient trials for analysis (Rothbart et al., 2003). Altogether these data support the existence of a link between attentional efficiency as evaluated by cognitive tasks and parent-reported measures of effortful control.

Another form of action monitoring is the detection and correction of errors. In our study, reaction times following an error in the Spatial Conflict task were 200 msec longer than those following a correct trial for 30-month-old children, and over 500 msec longer at 36 months, indicating that children were noticing their errors and using them to guide performance in the next trial. However, no evidence of slowing following an error was found at 24 months (Rothbart et al., 2003). A similar result with a different time frame was found when using a version of the Simple Simon game. In this task, children are asked to execute a response when a command is given by one stuffed animal while inhibiting responses commanded by a second animal (Jones, Rothbart, & Posner, 2003). Children of 36 to 38 months were unable to inhibit their response and showed no slowing following an error, but at 39 to 41 months, children showed both an ability to inhibit and a slowing of

TABLE 1

Development of Conflict Resolution Assessed With Different Conflict Tasks

		Congruent Trials		*Incongruent Trials*		*Conflict Effect*		
Age	*Task*	*RT*	*% Correct*	*RT*	*% Correct*	*RT*	*% Correct*	*Study Reference*
2	Spatial conflict	3,476	69.1	3,378	53.9	–98	–15.2	Rothbart, Ellis, Rueda, and Posner (2003)
2½	Spatial conflict	2,489	80.8	3,045	57.8	556	–23.0	Rothbart, Ellis, Rueda, and Posner (2003)
3	Spatial conflict	2,465	90.1	3,072	80.3	607	–9.8	Rothbart, Ellis, Rueda, and Posner (2003)
4	Flanker (child ANT)[a]	1,490	89.4	1,913	77.1	424	–13.0	Rueda, Posner, Rothbart, and Davis-Stober (2004)
6	Flanker (child ANT)	890	92.0	1,005	76.4	115	–15.6	Rueda, Fan, et al. (2004)
7	Flanker (child ANT)	828	94.6	891	93.9	63	–0.7	Rueda, Fan, et al. (2004)
8	Flanker (child ANT)	791	95.0	862	95.3	71	0.3	Rueda, Fan, et al. (2004)
9	Flanker (child ANT)	724	98.1	791	96.5	67	–1.6	Rueda, Fan, et al. (2004)
10	Flanker (child ANT)	624	98.7	693	96.6	69	–2.1	Rueda, Fan, et al. (2004)
Adults	Flanker (child ANT)	473	99.5	534	97.9	61	–1.6	Rueda, Fan, et al. (2004)

Note. Conflict effects are calculated by subtracting congruent from incongruent conditions. In all the studies, RT data are the means (across participants) of the median RT (per participant, in milliseconds).

[a] The stimuli used in this study were larger than in the Rueda, Fan, et al. (2004) study also using the child ANT, resulting in slightly smaller conflict scores.

reaction time following an error. These results suggest that between 30 and 39 months, children greatly develop their ability to detect and correct erroneous responses and that this ability may relate to the development of inhibitory control.

As discussed earlier, resolving conflict from competing stimulation also requires attentional control. We have recently adapted the ANT (Fan et al., 2002) for use with children as young as 4 years of age (Rueda, Fan, et al., 2004; see Figure 1). In this task, a row of five fish appears in the center of the screen, and the child's job is to help in "feeding" the middle fish by pressing the key corresponding to the direction in which the middle fish is pointing. On half the trials, the flanker fish are pointing in the same direction as the middle fish (congruent trials); on the other half, the flanker fish are pointing in the opposite direction (incongruent trials). The time to resolve conflict, calculated by subtracting the reaction time for congruent trials from the reaction time for incongruent trials, is a measure of conflict resolution. In a series of studies using this task, we have observed considerable development of conflict resolution between 4 and 7 years of age, but a striking consistency in performance after age 7 to adulthood (see Table 1).

To examine the brain mechanisms underlying differences in conflict resolution between children and adults, we have recently conducted an ERP study in which we used the fish flanker task with 4-year-old children and adults (Rueda, Posner,

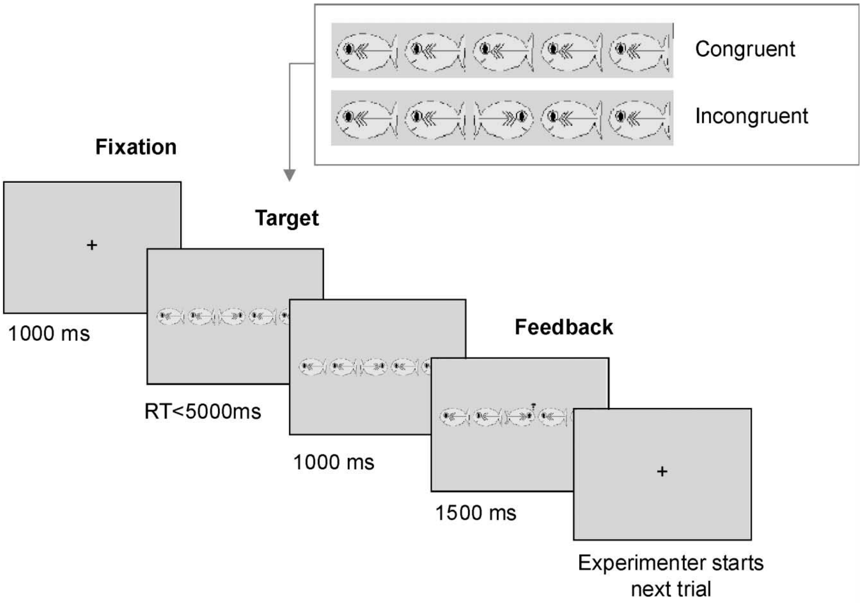

FIGURE 1 Schematic representation of the Flanker task in the Child ANT.

Rothbart, & Davis-Stober, 2004). Characteristics of the ERP make this technique amenable to children of all ages. In our study, we used a high-density system of electroencephalography (Tucker, 1993). This procedure allows evaluation of differences between children and adults in the time course of brain activations related to the task and provides a wide sampling of the distribution of activation over the scalp. As expected, we found the N2 effect for adults over the mid-frontal leads. The children's data also showed a larger negative deflection for the incongruent condition at the mid-frontal electrodes. Compared to adults, this effect had a larger size, had greater amplitude, and was extended over a longer period of time (see Figure 2).

Differences between children and adults in ERP amplitude have been related to brain size and skull thickening. Differences in the latency of components, however, may be related more to the large differences between adults and children in reaction time (431 msec vs. 1,614 msec) and conflict resolution times (30 msec vs. 424 msec). Whereas the frontal effect was evident for adults at around 300 msec posttarget, children did not show any effect until approximately 550 msec after the target. In addition, the effect was sustained over a period of 500 msec before the

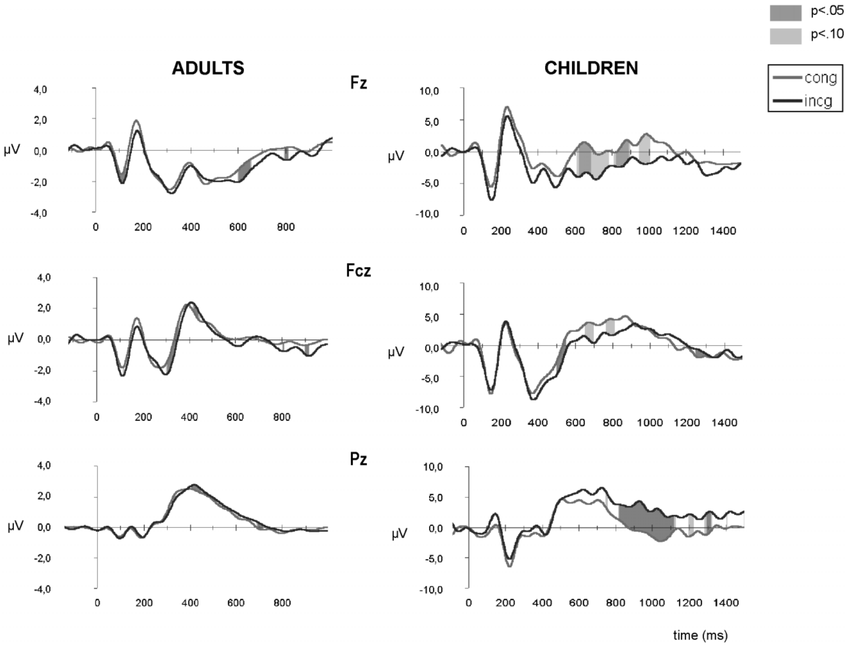

FIGURE 2 Adults' and 4-year-old children's ERPs obtained with the Child ANT at frontal (Fz), frontal-central (Fcz) and parietal (Pz) leads. Notice adult versus child differences in the scale of the graphs.

children's responses, in contrast with only 50 msec in the case of adults. The differences observed between children and adults over the frontal channels differed from other components observed at mid-parietal channels. For both children and adults, we found a greater positivity for incongruent trials over mid-parietal leads. For adults, this effect was observed at approximately 400 msec posttarget, in the time window of the P300, whereas it was more delayed in the case of children (between 800 and 1,100 msec posttarget). The P300 is thought to be an index of stimulus evaluation (Coles, Gratton, Bashore, Ericksen, & Donchin, 1985). This parietal effect could reflect developmental differences in the difficulty of evaluating the display depending on the congruence of surrounding flankers, whereas the frontal effect could reveal differences in the time course of conflict resolution.

Another important difference between 4-year-old children and adults was the distribution of effects over the scalp (see Figure 3). In adults, the frontal effects appear to be focalized on the midline, whereas in children the effects were observed mostly at prefrontal sites and in a broader number of channels, including the midline and lateral areas. In addition, the effect on the P3 appears to be left-lateralized in the adult data but lateralized to the right side in the children. The focalization of signals in adults as compared to children is consistent with neuroimaging studies conducted with older children, where children appear to activate the same network of areas as adults when performing similar tasks, but the average volume of activation appears to be remarkably greater in children compared to adults (Casey, Thomas, Davidson, Kunz, & Franzen, 2002; Casey et al., 1997; Durston et al., 2002). Altogether, these data suggest that the brain circuitry

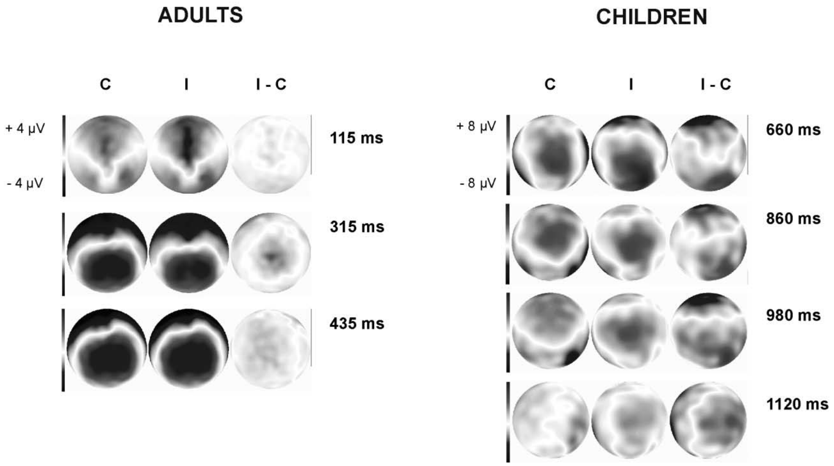

FIGURE 3 Adults and children's scalp topographic distributions of ERPs associated with congruent (C) and incongruent (I) conditions, and the conflict effect (I-C) at time points when significant effects (see Figure 2) were found.

underlying executive functions becomes more focal and refined as it gains in efficiency. This maturational process involves not only greater anatomical specialization but also reducing the time these systems need to resolve each of the processes implicated in the task.

PLASTICITY

Connections between self-regulation and the executive attention network place some emphasis on the biological processes underpinning the efficiency of control systems. However, the role of experience in brain development is not to be neglected (Bavelier & Neville, 2002; Neville & Bavelier, 1999). Examples of brain plasticity as shown by training-induced increases in performance can be found in both children and adults. Several training oriented programs have resulted in improved executive control in patients with specific brain injury. The use of Attention Process Training (APT) has led to specific improvements in executive attention in tasks quite remote from those that have undergone training (Sohlberg, McLaughlin, Pavese, Heidrich, & Posner, 2000). Other studies suggest that the effects of training may depend on first establishing a minimum level of alerting and orienting capacities (Sturm, Willmes, Orgass, & Hartje, 1997). The APT has also proven successful in training attentional abilities in children with ADHD (Kerns, Esso, & Thompson, 1999; Semrud-Clikeman, Nielsen, & Clinton, 1999). With normal adults, training with video games has been shown to produce better performance on a range of visual attention tasks (Green & Bavelier, 2003).

We have tested whether specific attention training during the development of executive attention in 4 year olds can influence the efficiency with which this network is activated (Rueda, Rothbart, McCandliss, Saccamono, & Posner, 2005). We have designed a set of computerized training exercises to help preschool children develop their executive attention skills. The program begins with training the child to control the movement of an animated cat on a computer screen by using a joystick. Other exercises involve prediction of where an animated figure will move given its initial trajectory, retention of information for a matching to sample task, and the resolution of conflict. The exercises were designed to be completed in five 45-min sessions conducted over a 2- to 3-week period. Behavioral and electrophysiological measures of executive attention (Child ANT; Rueda, Fan, et al., 2004), general intelligence (Kaufman Brief Intelligence Test [K-BIT]; Kaufman & Kaufman, 1990), and temperament (CBQ; Rothbart et al., 2001) were used in assessment sessions conducted before and after training. Children were randomly assigned to an experimental group that underwent training or to a control group that did not. The experimental group showed more adultlike conflict scores following training than did the control group. Although some or all of this effect might have been due to differences in the pretest, we also found that following training, the experimental group was the only group showing a pattern in the N2 component of the ERPs similar to the one shown by adults (see Figure 4; Rueda et al., 2005).

The training also produced significant increases in overall IQ, mostly due to increasing the score in the Visual Matrices scale measured by the K-BIT. Other forms of attention training for children with ADHD have also improved performance on abstract reasoning as measured by Raven's Progressive Matrices (Klingsberg, Forssberg, & Westerberg, 2002), suggesting that training of attention may benefit cognitive functioning extending over a range of tasks. The fact that training on executive attention may result in improvement of general intelligence is not very surprising, considering their common anatomies (Duncan et al., 2000).

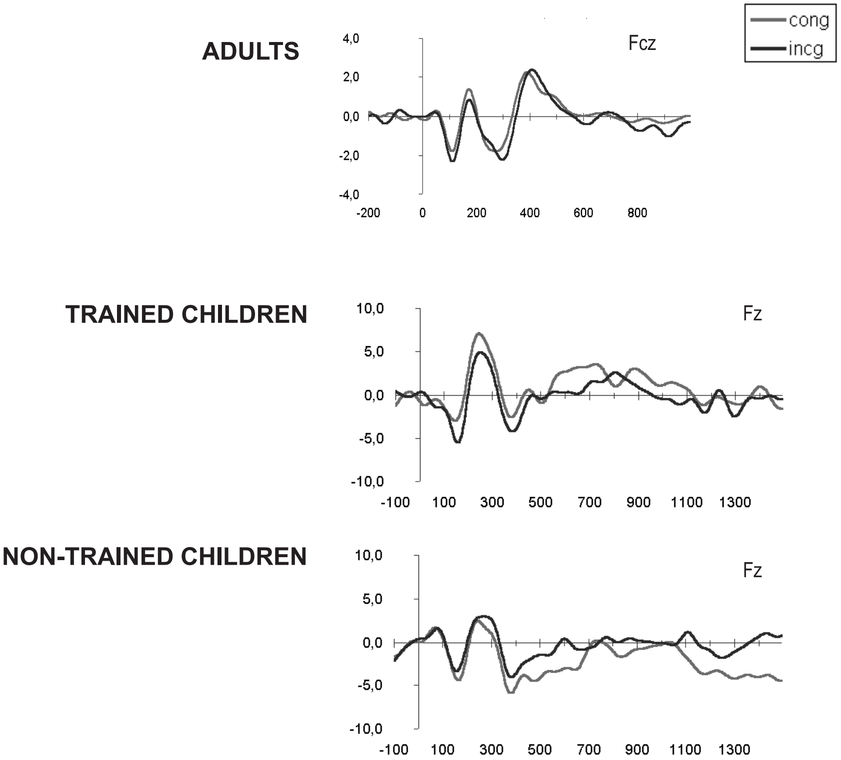

FIGURE 4 Comparison of the ERPs of adults and the trained and control (nontrained) groups of 4-year-old children involved in the attention training study. All ERPs were obtained while participants were performing the Child ANT. Notice adult versus child differences in the scale of the graphs.

Although these results need to be replicated and extended, they suggest that the brain mechanisms associated with attentional control can be improved by training and that this improvement produces a benefit in behavioral measures of competence. Given the connection between attention and self-regulation, plasticity of the neural system underlying executive attention opens a window for fostering self-regulation in young children. In our study, the short time period elapsing between the pre- and postassessment sessions did not allow for examining changes in reported temperament scores related to effortful control. Studies specifically testing the benefits of training of attention on the ability of children to control their behavior remain to be done.

CONCLUSION

In cognitive models, attention has been traditionally involved in the control of intended actions. In this sense, attentional control has been identified as an important domain in self-regulation (Posner & Rothbart, 1998; Rueda, Posner, & Rothbart, 2004). With the emergence of cognitive neuroscience, numerous studies have combined the use of simple but theoretically grounded cognitive tasks with neuroimaging techniques and have greatly extended our understanding of the neural system supporting attentional control. Conflict tasks (e.g., Flanker, Stroop, and Spatial Conflict tasks) have been widely used to study this form of control. A network of brain areas, referred to as the executive attention network, is primarily active in tasks that involve conflict resolution. This network includes the ACC and lateral prefrontal cortex.

We have used conflict tasks adapted to children to study the development of executive attention. In our studies, we have combined the use of laboratory tasks with parent-reported questionnaires and with techniques for assessment of brain function amenable to young children. The ability to deal with conflict in young children appears to relate to parent-reported measures of effortful control, supporting the connection between executive attention and self-control skills. We have found considerable improvement in the ability to resolve conflict between 2 and 5 years of age, and continuous improvement up to 7 years, when children appear to reach the adult level of performance, at least when using the Child ANT (see Table 1). Consistent with the much greater difficulty for children to resolve conflict, we have found longer latencies and sustained conflict effects on children's evoked potentials compared to adults. It is of interest that the pattern of electrophysiological activity seems to be susceptible to modulation through attention training. This result shows the potential of cognitive and behavioral training for fostering brain processes related to attentional control. Considering executive attention as a system for the voluntary control of action, the benefits of training attention could extend to greater cognitive and emotional regulation of children's behavior.

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REFERENCES

Bavelier, D., & Neville, H. J. (2002). Cross-modal plasticity: Where and how? *Nature Reviews Neuroscience, 3,* 443–452.

Beauregard, M., Levesque, J., & Bourgouin, P. (2001). Neural correlates of conscious self-regulation of emotion. *Journal of Neuroscience*, *21,* 6993–7000.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402,* 179–181.

Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in the anterior cingulate cortex. *Trends in Cognitive Science, 4/6,* 215–222.

Carlson, S. T., & Moses, L. J. (2001). Individual differences in inhibitory control in children's theory of mind. *Child Development, 72*, 1032–1053.

Carlson, S. M., Moses, L. J., & Claxton, L. J. (2004). Individual differences in executive functioning and theory of mind: An investigation of inhibitory control and planning ability. *Journal of Experimental Child Psychology, 87,* 299–319.

Casey, B. J., Durston, S., & Fossella, J. A. (2001). Evidence for a mechanistic model of cognitive control. *Clinical Neuroscience Research, 1,* 267–282.

Casey, B. J., Thomas, K. M., Welsh, T. F., Badgaiyan, R. D., Eccard, C. H., Jennings, J. R., et al. (2000). Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging. *Proceeding of the National Academy of Sciences, USA, 97,* 8728–8733.

Casey, B. J., Thomas, K. M., Davidson, M. C., Kunz, K., & Franzen, P. L. (2002). Dissociating striatal and hippocampal function developmentally with a Stimulus-Response compatibility task. *Journal of Neuroscience, 22,* 8647–8652.

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., et al. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of Cognitive Neuroscience, 9,* 835–847.

Clohessy, A. B., Posner, M. I., & Rothbart, M. K. (2001). Development of the functional visual field. *Acta Psychologica, 106,* 51–68.

Coles, M. G. H., Gratton, G., Bashore, T. R., Ericksen, C. W., & Donchin E. (1985). A psychopsysiologicl investigation of the continuous flow model of human information processing. *Journal of Experimental Psychology: Human, Perception & Performance, 11,* 529–553.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Neuroscience Reviews, 3,* 201–215.

Dagenbach, D., & Carr, T. H. (Eds.). (1994). *Inhibitory processes in attention, memory, and language.* San Diego, CA: Academic.

Derryberry, D., & Reed, M. A. (1998). Anxiety and attentional focusing: Trait, state and hemispheric influences. *Personality & Individual Differences, 25,* 745–761.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Diamond, A. (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 67–110). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Diamond, A., Briand, L., Fossella, J., & Gehlbach, L. (2004). Genetic and neurochemical modulation of prefrontal cognitive functions in children. *American Journal of Psychiatry, 161,* 125–132.

Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus monkeys on Piaget's A-not-B task: Evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research, 74,* 24–40.

Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., et al. (2000). A neural basis for general intelligence. *Science, 289,* 457–460.

Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science, 5,* F9–F16.

Egan, M. F., Goldberg, T. E., Kolachana, B. S., Callicott, J. H., Mazzanti, C. M., Straub, R. E., et al. (2001). Effect of COMT val$^{108/158}$ met genotype of frontal lobe function and risk for schizophrenia. *Proceedings of the National Academy of Sciences, USA, 98,* 6917–6922.

Eisenberg, N., Fabes, R. A., Nyman, M., Bernzweig, J., & Pinulas, A. (1994). The relations of emotionality and regulation to children's anger-related reactions. *Child Development, 65,* 109–128.

Eisenberg, N., Smith, C. L., Sadovsky, A., & Spinrad, T. L. (2004). Effortful control: Relations with emotion regulation, adjustment, and socialization in childhood. In R. F. Baumeister & K. D. Vohs (Eds.), *Handbook of self regulation*: *Research, theory, and applications* (pp. 259–282). New York: Guilford.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16,* 143–149.

Fan, J., Flombaum, J. I., McCandliss, B. D., Thomas, K. M., & Posner, M. I. (2003). Cognitive and brain consequences of conflict. *NeuroImage, 18,* 42–57.

Fan, J., Fossella, J. A., Sommer, T., & Posner, M. I. (2003). Mapping the genetic variation of executive attention onto brain activity. *Proceedings of the National Academy of Sciences, USA, 100,* 7406–7411.

Fan, J., McCandliss, B. D., Sommer, T., Raz, M., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 340,* 340–347.

Fan, J., Wu, Y., Fossella, J., & Posner, M. I. (2001). Assessing the heritability of attentional networks. *BioMed Central Neuroscience, 2,* 14.

Fonagy, P., & Target, M. (2002). Early intervention and the development of self-regulation. *Psychoanalytic Quarterly, 22,* 307–335.

Fossella, J., Posner, M. I., Fan, J., Swanson, J. M., & Pfaff, D. M. (2002). Attentional phenotypes for the analysis of higher mental function. *The Scientific World Journal, 2,* 217–223.

Fuentes, J. J. (2004). Inhibitory processing in the attentional networks. In M. I. Posner (Ed.), *Cognitive neuroscience of attention* (pp.45–55). New York: Guilford.

Gehring, W. J., Gross, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4,* 385–390.

Gerardi-Caulton, G. (2000). Sensitivity to spatial conflict and the development of self-regulation in children 24–36 months of age. *Developmental Science, 3/4,* 397–404.

Goldberg, T. E., & Weinberger, D.R. (2004). Genes and the parsing of cognitive processes. *Trends in Cognitive Science, 8,* 325–335.

Granon, S., Passetti, F., Thomas, K. L., Dalley, J. W., Everitt, B. J., & Robbins, T. W. (2000). Enhanced and impaired attentional performance after infusion of D1 dopaminergic receptor agents into rat prefrontal cortex. *Journal of Neuroscience, 20,* 1208–1215.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423,* 534–537.

Harman, C., Rothbart, M. K., & Posner, M. I. (1997). Distress and attention interactions in early infancy. *Motivation and Emotion, 21,* 27–43.

Houghton, G., & Tipper, S. P. (1994). A model of inhibitory mechanisms in selective attention. In D. Dagenbach & T. Carr (Eds.), *Inhibitory mechanisms in attention, memory, and language* (pp. 53–112). Orlando, FL: Academic.

Jackson, S. R., Jackson, G. M., & Roberts, M. (1999). The selection and suppression of action: ERP correlates of executive control in humans. *NeuroReport, 10,* 861–865.

James, W. (1890). *The principles of psychology*. New York: Holt.

Jones, L. B., Rothbart, M. K., & Posner, M. I. (2003). Development of executive attention in preschool children. *Developmental Science, 6,* 498–504.

Joober, R., Gauthier, J., Lal, S., Bloom, D., Lalonde, P., Rouleau, G., et al. (2002). Catechol-O-methyltransferase Val-108/158-Met gene variants associated with performance on the Wisconsin Card Sorting Test. *Archives of General Psychiatry, 59,* 662–663.

Kaufman, A. S., & Kaufman, N. L. (1990). *Kaufman Brief Intelligence Test–Manual*. Circle Pines, MN: American Guidance Service.

Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review, 110,* 316–339.

Kerns, K. A., Esso, K., & Thompson, J. (1999). Investigation of a direct intervention for improving attention in young children with ADHD. *Developmental Neuropsychology, 16,* 273–295.

Klingsberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology, 24,* 781–791.

Kochanska, G. (1991). Socialization and temperament in the development of guilt and conscience. *Child Development, 62,* 1379–1392.

Kochanska, G. (1995). Children's temperament, mothers' discipline, and security of attachment: Multiple pathways to emerging internalization. *Child Development, 66,* 597–615.

Kochanska, G. (1997). Multiple pathways to conscience for children with different temperaments from toddlerhood to age 5. *Developmental Psychology*, *3,* 228–240.

Kochanska, G., Murray, K. T., & Harlan, E. T. (2000). Effortful control in early childhood: Continuity and change, antecedents, and implications for social development. *Developmental Psychology, 36,* 220–232.

Kochanska, G., Murray, K., Jacques, T. Y., Koenig, A. L., & Vandegeest, K. A. (1996). Inhibitory control in young children and its role in emerging internationalization. *Child Development, 67,* 490–507.

Kopp, B., Rist, F., & Mattler, U. (1996). N200 in the flanker task as a neurobehavioral tool for investigating executive control. *Psychophysiology, 33,* 282–294.

Neville, H. J., & Bavelier, D. (1999). Specificity and plasticity in neurocognitive development in humans. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (2nd ed., pp. 83–98). Cambridge, MA: MIT Press.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, C. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (pp. 1–18). New York: Plenum.

Ochsner, K. N., Bunge, S. A., Gross, J. J., & Gabrieli, J. D. E. (2002). Rethinking feelings: An fMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience, 14,* 1215–1229.

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in Neuroscience, 7,* 75–79.

Posner, M. I., & DiGirolamo, G. J. (1998) Executive attention: Conflict, target detection, and cognitive control. In R. Parasuraman (Ed.), *The attentive brain* (pp. 401–423). Cambridge, MA: MIT Press.

Posner, M. I., & Fan, J. (in press). Attention as an organ system. In J. Pomerantz (Ed.), *Neurobiology of perception and communication: From synapse to society. The IVth De Lange Conference.* Cambridge, England: Cambridge University Press.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13,* 25–42.

Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York: Scientific American Books.

Posner, M. I., & Raichle, M. E. (Eds.). (1998). Overview: The neuroimaging of human brain function. *Proceedings of the National Academy of Sciences, USA, 95,* 763–764.

Posner, M. I., & Rothbart, M. K. (1992). Attention and conscious experience. In A. D. Milner & M. D. Rugg (Eds.), *The neuropsychology of consciousness* (pp. 91–112). London: Academic.

Posner, M. I., & Rothbart, M. K. (1998). Attention, self-regulation, and consciousness. *Philosophical Transactions of the Royal Society of London, B, 353,* 1915–1927.

Rothbart, M. K., Ahadi, S. A., & Hershey, K. L. (1994). Temperament and social behavior in childhood. *Merrill-Palmer Quarterly, 40,* 21–39.

Rothbart, M. K., Ahadi, S. A., Hershey, K., & Fisher, P. (2001). Investigations of temperament at three to seven years: The Children's Behavior Questionnaire. *Child Development, 72,* 1394–1408.

Rothbart, M. K., Ellis, L. K., Rueda, M. R., & Posner, M. I. (2003). Developing mechanisms of conflict resolution. *Journal of Personality, 71,* 1113–1143.

Rothbart, M. K., Posner, M. I., & Boylan, A. (1990). Regulatory mechanisms in infant development. In J. Enns (Ed.), *The development of attention: Research and theory* (pp. 139–160). Amsterdam: Elsevier.

Rothbart, M. K., & Rueda, M. R. (2005). The development of effortful control. In U. Mayr, E. Awh, & S. W. Keele (Eds.), *Developing individuality in the human brain: A tribute to Michael I. Posner* (pp. 167–188). Washington, DC: American Psychological Association.

Rueda, M. R., Fan, J., McCandliss, B., Halparin, J. D., Gruber, D. B., Pappert, L., et al. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42,* 1029–1040.

Rueda, M. R., Posner, M. I., & Rothbart, M. K. (2004). Attentional control and self regulation. In R. F. Baumeister & K. D. Vohs (Eds.), *Handbook of self regulation*: *Research, theory, and applications* (pp. 283–300). New York: Guilford.

Rueda, M. R., Posner, M. I., Rothbart, M. K., & Davis-Stober, C. P. (2004). Development of the time course for processing conflict. An ERP study with 4 year olds and adults. *BMC Neuroscience, 5,* 39.

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccamono, L., & Posner, M. I. (2005). *Relative influences of training, maturation and genetic differences in the development of executive attention.* Manuscript submitted for publication.

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in early development: Themes and variations*. New York: Oxford University Press.

Seamas, J. K., Floresco, S. B., & Phillips, A. G. (1998). D_1 receptor modulation of hippocampal-prefrontal cortical circuits integrating spatial memory with executive functions in the rat. *Journal of Neuroscience, 18,* 1613–1621.

Semrud-Clikeman, M., Nielsen, K. H., & Clinton, A. (1999). An intervention approach for children with teacher and parent-identified attentional difficulties. *Journal of Learning Disabilities, 32,* 581–589.

Sohlberg, M. M., McLaughlin, K. A., Pavese, A., Heidrich, A., & Posner, M. I. (2000). Evaluation of attention process therapy training in persons with acquired brain injury. *Journal of Clinical and Experimental Neuropsychology, 22,* 656–676.

Sturm, W., Willmes, K., Orgass, B., & Hartje, W. (1997). Do specific attention deficits need specific training? *Neuropsychological Rehabilitation, 7,* 81–103.

Swanson, J., Oosterlaan, J., Murias, M., Moyzis, R., Schuck, S., Mann, M., et al. (2000). ADHD children with 7-repeat allele of the DRD4 gene have extreme behavior but normal performance on critical neuropsychological tests of attention. *Proceedings of the National Academy of Sciences, USA, 97,* 4754–4759.

Tucker, D. M. (1993). Spatial sampling of head electrical fields: The geodesic sensor net. *Electroencephalography and Clinical Neurophysiology: Evoked Potentials, 87,* 154–163.

van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14,* 593–602.

Vohs, K. D., & Baumeister, R. F. (2004). *Handbook of self regulation*: *Research, theory, and applications.* New York: Guilford.

Welch, M. C. (2001). The prefrontal cortex and the development of the executive function in childhood. In A. F. Kalverboer & A. Gramsbergen (Eds.), *Handbook of brain and behavior in human development* (pp. 767–790). Dordrecht, The Netherlands: Kluwer Academic.