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Developing mechanisms of self-regulation

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Abstract
Child development involves both reactive and self-regulatory mechanisms that children develop in conjunction with social norms. A half-century of research has uncovered aspects of the physical basis of attentional networks that produce regulation, and has given us some knowledge of how the social environment may alter them. In this paper, we discuss six forms of developmental plasticity related to aspects of attention. We then focus on effortful or executive aspects of attention, reviewing research on temperamental individual differences and important pathways to normal and pathological development. Pathologies of development may arise when regulatory and reactive systems fail to reach the balance that allows for both self-expression and socially acceptable behavior. It remains a challenge for our society during the next millennium to obtain the information necessary to design systems that allow a successful balance to be realized by the largest possible number of children.

We believe that understanding self-regulation is the single most crucial goal for advancing an understanding of development and psychopathology. Early in this century, Freud (1920) argued that the ego and superego developed to regulate largely unconscious motivational systems. In the latter part of this century, mechanisms of self-regulation have begun to be uncovered through the study of attention and effortful control. There is also substantial reason to believe that understanding mechanisms of self-regulation in normal individuals will lead to advances in diagnosis, prevention, and possibly treatment of developmental problems like attention deficit disorder and learning disabilities. In turn, studies of these mechanisms in the developmental disorders will enhance our understanding of normal functioning.

Self-regulation involves complex questions about the nature of volition and its relation to our genetic endowment and to social experience. Much of the work on self-regulation has been purely behavioral. This is true in both attention studies carried out within cognitive psychology and studies of effortful control as a temperamental dimension. The lack of appropriate methods to study the physiology of the human brain has previously led to an understandable hesitation in thinking about these processes at the neurosystems level. Kandel (1998, 1999), however, has argued persuasively that new concepts in neuroscience now make it possible to attempt to relate higher level cognitive concepts to underlying brain systems. His goal is to use modern neuroscience to reinvigorate the psychoanalytic approach to the mind, and he stresses the role of unconscious early experience in shaping the brain systems that control adult behavior. Even if such connections prove to be as yet premature, there is little question that they will be major topics in the coming years.

A major goal of our paper is to help the reader understand how new developments re-

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lated to neural plasticity and neuroimaging have transformed the potential for understanding mechanisms that provide voluntary control of brain systems. While Kandel (1998, 1999) has emphasized the relation of genetic and cellular processes to psychoanalytic concepts and therapy, our article concentrates mainly at the neurosystems level and deals with the mechanisms that produce voluntary control of our thoughts and actions.

Discoveries within neuroscience have moved the field toward viewing the brain as plastic and open to influence by experience (Garraghty, Churchill, & Banks, 1998; Merzenich & Jenkins, 1995). The advent of neuroimaging has provided new tools for testing hypotheses about how the brain changes with experience and for exploring the behavioral mechanisms of self-regulation (Posner & Raichle, 1994). In this article we first examine some of the historical background for considering attention networks as mechanisms of self-regulation in the human brain. Next, we take advantage of imaging methods to examine how the brain might be altered by experience on a time scale from milliseconds to years. We then examine the role of high-level attentional networks as a vehicle for self-regulation and consider evidence that similar brain areas control regulation of emotion and cognition. We consider how individuals differ in effortful control and what some of the consequences of those differences might be for normal and pathological development. In our final section, we speculate on future developments in this field.

History

Within cognitive psychology, the mechanisms thought to be involved in self-control are collectively called attention. In 1958, Donald Broadbent summarized British work in the field of attention in his volume *Perception and Communication*. He proposed a filter that held back messages from an unattended channel to keep them from interfering with selected input. Broadbent's beautiful studies, summarized in nearly every textbook in psychology, provided a basis for studying how we make a selection of relevant information from the masses of potential input. The studies reviewed in his book viewed attention as a high-level skill that allowed some experts to perform selective feats such as simultaneous translation and even novices to have a role in selecting their environment.

There were challengers to Broadbent's ideas, but it is remarkable, in view of the 4 decades that have passed since 1958, how even his strongest critics have followed his general ideas. For example, Anne Treisman (1969) showed that the filter could better be described as an attenuator, with much less interference when input was to separate modalities (eye and ear), rather than to one. Norman (1969) argued it would be better to see the filter as operating later in the system, after input had already activated material stored in long-term memory. Indeed, experiments rather quickly established that familiar words could look up their meanings even prior to being perceived (Posner, 1978). Allport (1980) challenged whether limited capacity was related to attention, and argued that interference instead resulted from contradicting behavioral task demands. However, all of the ideas about attention that dominated cognitive journals for the last half century were clearly derivatives of the basic question Broadbent (1958) had posed about selective listening: How was it that some aspects of the input were perceived and others not? The connection between selective processes in perception and more general issues of self-regulation had to await a link between cognitive and the neurophysiological level of analysis.

An important early link between studies of attention within human cognition and those using the methods of neurophysiology was provided by Sokolov (1963) in his treatment of the orienting reflex. The orienting reflex provided a physical basis for filtering input and presaged the intense interest within neurophysiology in how attention might modulate activity within sensory specific areas (Hillyard & Lourdes, 1998). The concept of the orienting reflex was readily adapted to the study of preverbal infants who could not be instructed as to where to attend by experimenters (see review by Ruff & Rothbart, 1996). Ruff and Rothbart (1996) identify

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landmark periods in the 1st year of life with regard to orienting to objects and control of distress and in the 2nd year and beyond in children's ability to plan and regulate cognitive skills.

It was a relatively easy step to identify these changes in the ability of the child to regulate behavior with the development of brain areas that carried out attentional selection in adults. This step, however, has a powerful consequence. It allows us to transfer knowledge on the anatomy and circuitry of attentional networks (Posner & Raichle, 1994) to the development of orienting and regulation in infants and adults (Posner & Rothbart, 1998), providing mechanisms for understanding self-regulation and its development. Below, we consider changes in the human brain that might reflect both the rapid switch of content that occurs when adult subjects shift the focus of their attention and the much slower accumulation of the ability to control attention that occurs over the early years of development.

Plasticity

In neuroscience, the issue of plasticity in brain activity has been discussed mainly at the synaptic level. For example, correlated neural firing among neurons in contact with each other leads to a change in the probability of one neuron being able to induce firing in the other. This principle of learning, first discussed by Hebb (1949), has been shown to be a basic principle for synaptic plasticity.

The use of neuroimaging methods, however, has provided an altogether different level of analysis of plasticity. Instead of individual synapses, the focus is on the question of how experience influences the set of neural areas active within a task and their time course of activation. This work has begun to allow us to consider possible neural mechanisms for many of the kinds of changes involved in children's learning and education. Table 1 indicates some of the ways in which the person's own activity or learning from external-based events might work to change brain circuitry on a temporary or more permanent basis.

The top row of Table 1 refers to the finding that attention allows rapid changes in neural activity in local brain areas. Neuroimaging methods are sensitive to changes in blood flow that accompany neural activity. When a brain area is being used to perform computations in high-level skills, it will increase in activity (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990). As children learn a new skill, they may show a high level of variability as they try different strategies (Siegler, 1997). Each of these strategies is represented by a connected set of neural areas that carry out particular computations in some order. In adult studies, it is possible to demonstrate how a particular strategy may assume momentary dominance. Attention can provide priority to some computations, reprogramming the organization of the circuits by which tasks are executed. Priority is produced by amplifying the amount of neural activity within the area performing the computation. Often this is done voluntarily, as one tries to select a set of operations that seem most appropriate to a given task. This is what we call effortful control by attention.

However, strategies may also arise from the physical situation. In the presence of a calculator, the person may enter numbers and press the appropriate key. If the calculator is absent, the numbers may be written down and the operations perform mentally. In this way, the environment primes one network of areas rather than another. Priming (row 2 of Table 1) is produced by the presentation of a sensory event (e.g., the calculator mentioned above), or by thought (e.g., the activation of a visual or auditory word), which changes the processing pathway so that stimuli sharing some or the entire pathway will be processed more efficiently. Priming can produce reduced reaction time for responding to a related target that follows the prime. Neuroimaging and cellular studies suggest that the number of neurons activated by a primed target is reduced over those activated in nonprimed target processing. The prime apparently tunes the neurons involved in the target event so that only those most appropriate to processing the subsequent target are activated (Ungerleider, Courtney, & Haxby, 1998).

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Table 1. *Mechanisms of plasticity*

Time	Phenomenon	Mechanism	Reference
1. Milliseconds	Shifts in attention	Amplification	Corbetta et al. (1990)
2. Seconds to minutes	Priming	Tuning	Jiang et al. (2000)
3. Minutes to days	Practice	Pathway	Raichle et al. (1994)
4. Weeks	New associations	Connections	McCandliss et al. (1997)
5. Weeks	Rule learning	Structures	McCandliss et al. (1997)
6. Years	Development	Attention networks	Posner & Rothbart (1998)

The mechanisms of rows 1 (attention shifts) and 2 (priming) of Table 1 provide two means to improve the processing of a target. The first method requires the person to attend to the computation. The involvement of attention sets up a network for processing the stimulus, but at the cost of making attention less available for handling other events. Priming, however, may occur when attention is now no longer involved in the process, leaving it free to deal with other items. Nevertheless, the network remains active for a period to make the processing of previously attended computations available. Priming may also occur without attention as the result of a sensory process. A pathway that has been tuned by a priming event does not require current attention and thus does not produce interference with ongoing activity (Posner, 1978). Effortful control through attention and automatic pathway activation apparently achieve the same behavioral results by quite different underlying mechanisms.

Practice on a set of already learned but not recently rehearsed associations (row 3 of Table 1) shows that automaticity can completely change the pathway used to accomplish the task. In one study using PET (Raichle, Fiez, Videen, MacLeod, Pardo, Fox, & Petersen, 1994), people were required to generate a use for a read or heard noun (e.g., pound as a use for a hammer). When a new list of words was presented there was activity in the left frontal and posterior cortex, the anterior cingulate, and the right cerebellum. Activity in the anterior insula was reduced over what was found in simply reading the words aloud. A few minutes of practice at generating an associated use shifted activation so that the left frontal and posterior areas important in generating a new use dropped away and the anterior insula, strongly activated during reading aloud, increased. When generating a given word became automated with practice, the same circuit was used as when skilled readers read words aloud. There appeared to be one circuit associated with the thought needed to generate a familiar but unpracticed use, and another when the task was automated, as in reading aloud or generating again a just practiced association. The circuit used for thought includes attentional mechanisms involving effortful control, while an automated circuit does not involve attention.

In the study cited above, people are dealing with already well-known associations, as, for example, the association between hammer and pound. Even when they have not practiced them recently, connections between hammer and pound are available. However, it is often necessary to acquire entirely new associations, as in learning the words of a foreign language. This involves establishing new connections in the brain (row 4 of Table 1) and may require many weeks of practice. In one study of learning 40 lexical items in a new artificial language, it took 20–50 hr of practice before the words showed the same superiority in reaction time usually found for reading the native language (McCandliss, Posner & Givon, 1997).

Even more complex than learning a few new associations is developing a whole system to carry out an important linguistic function (row 5 of Table 1). Studies using PET with literate adults have shown that areas of the visual system of the brain become active when strings of letters are possible words in English, whether they have meaning or not (Petersen, Fox, Snyder & Raichle, 1990). This

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area of the brain is not active for nonsense strings like a series of consonants. It seems to represent English orthography and has been called the visual word form system (Petersen et al., 1990). This system appears to be a left posterior function that serves to group letters of a word automatically into a single chunk. No such unified chunk occurs for a string of consonants. This system appears to require some years to develop. Evidence suggests it is not present in 7-year-olds, even in those who know how to read, and can be found in 10-year-olds to a limited degree. Moreover, once this system is developed, it appears to be strongly resistant to change (Posner & McCandliss, in press).

The final row of Table 1 refers to changes in brain structures that develop over the early life span of the person. We have in mind the several years apparently required to develop attentional networks. One form of attentional control deals with the selection of information by orienting to a sensory modality or location (e.g., eye movements or shifts of visual attention in vision). Orienting shows marked development in the 1st year of life (Ruff & Rothbart, 1996). In the visual system, early development includes improvements in acuity, control of fixation, ability to disengage, preference for novel objects and locations, and the control of emotional distress (Ruff & Rothbart, 1996). A second form of attention shows strong development in the 2nd year of life and after (Posner & Rothbart, 1998). It provides the child with the necessary independence from their sensory world to develop an agenda of their own. The development of this system and its significance for the child are described further below.

Executive Control

The central issue of this section is to describe an approach for examining executive function as a developmental process in early childhood. The goal is to provide an experimental means to link individual differences in self-regulatory behaviors developing in early childhood to the maturation of underlying neural systems. Norman and Shallice (1986) developed a model of adult attention very much in the spirit of the Broadbent approach. They argued that a supervisory attention system comes into play in adults in resolving conflict, correcting errors, and planning new actions. There now appears to be excellent data that the ability to resolve conflict undergoes development in early childhood.

Adult studies using positron emission tomography (PET) have been consistent in showing activity in midline frontal areas during tasks that might be thought to involve executive attention (Bush, Whalen, Rose, Jenike, McInerney, & Rauch, 1998; Posner & DiGirolamo, 1998). One such task we have already discussed is generating the use of a word. When blood flow due to reading words aloud is subtracted from blood flow in generating a use, there is a strong activation in the frontal midline along with language related areas of the left hemisphere and in connected areas in the cerebellum. Subsequent studies using high-density electrical recording have shown that midfrontal activity is detected very early, about 150 ms after input. This suggests that the first activity involves marshaling the cognitive effort needed to generate a use beyond that needed in the relatively effortless task of reading aloud. This view also agrees with PET studies showing that midfrontal activity may occur even before the task starts, when subjects know that a difficult task will occur (Murtha, Chertkow, Beauregard, Dixon, & Evans, 1996).

The most frequently studied task found to activate the frontal midline has been the Stroop effect. In this task, subjects must respond to one dimension of a stimulus (usually the ink color), while ignoring another prepotent dimension (usually the color word name). A summary of the many results on Stroop effect conflict shows a remarkable convergence on areas of the frontal midline in the anterior cingulate gyrus (Bush et al., 1998).

Since the anterior cingulate is the major outflow of the limbic system, however, it seems reasonable that its main function would be related to emotion, not cognition, and there is clear evidence that anterior cingulate activity is a part of the brain's system for evaluating pain (Rainville, Duncan, Price, Carrier, & Bushness, 1997) and for distress vocalization

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(Devinsky, Morrell, & Vogt, 1995). The pain studies have shown cingulate activity when heat stimuli were judged as painful in comparison to merely warm. Moreover, the cingulate activity appears to be more related to the amount of subjective distress caused by the pain than to the intensity of the sensory stimuli involved (Rainville et al., 1997). When an effort was made to control the distress produced by a given stimulus using hypnotic suggestion, the amount of anterior cingulate activation reflected felt distress, while the somatosensory cortex reflected stimulus intensity.

Recent studies of negative emotion in adults have suggested that distress is also related to activity in the amygdala (Davidson & Sutton, 1995). When pictures depicting frightening or horrible scenes are shown to subjects, there is strong activation of the amygdala, and evidence now exists that activation of the amygdala can be modulated by frontal activity (Davidson & Sutton, 1995).

There is some evidence that cingulate activity is related to our awareness of emotion rather than to the emotion itself. To measure emotional awareness, people are asked to describe how they feel about situations. Their written responses are coded for use of emotional terms and descriptors (Lane & Schwartz, 1992) and the resultant score is taken as a measure of their emotional awareness. In a recent study, twelve subjects were shown each of three highly emotional movies and three neutral movies during a PET scan (Lane, Reiman, Ahern, Schartz, Davidson, Axelrod, & Yun, 1996). Differences in anterior cingulate blood flow between the emotional and neutral movies were positively related to the person's level of emotional awareness. These data suggest that something about awareness of emotions during sad or happy events is related to changes in the anterior cingulate. This result is similar to the finding discussed above indicating that cingulate activity is more related to the painful feelings than to the intensity of the stimulus inducing the pain (Rainville et al., 1997).

Control of distress is a major task for the infant and caregiver in the early months of life, and attention plays an important role in this regulation (Harman, Rothbart & Posner, 1997). In the first few months, caregivers help control distress mainly by holding and rocking. Increasingly, in the early months, visual orienting is also used. Caregivers then attempt to involve the child in activities that will occupy their attention and reduce their distress. These interactions between infant and caregiver may train the infant in control of distress and lead to the development of the midfrontal area as a control system for negative emotion. Later, when similar cognitive challenges arise, a system for regulating remote brain areas may be already prepared.

Many psychologists agree with Denckla (1996) that "the difference between the child and adult resides in the unfolding of executive functions" (p. 264). Luria (1973) also referred to the development of a higher level voluntary social attention system. More voluntary attentional mechanisms and individual differences in executive attention have important implications for the early development of behavioral and emotional control (Rothbart & Bates, 1998).

In an early example of cognitive control in a limited domain, Diamond (1991) showed the stages from 9 to 12 months in the child's resolving conflict between reaching along the line of sight in order to retrieve an object in a box. At 9 months, the line of sight dominates completely. Even if the infant's hand touches the toy through the open side of the box, if its movement is not in line with the side the child is looking at, the infant will withdraw the hand and reach along the line of sight, striking the closed side. Three months later, infants are able to look at a closed side but reach through the open end to retrieve the toy.

However, being able to reach for a target away from the line of sight is only a very limited form of conflict resolution. Gerstadt, Hong, and Diamond (1994) studied verbal conflict modeled on the Stroop paradigm in children as young as 3.5 years. Two cards were prepared to suggest day and night to the children: one depicted a line drawing of the sun, the other a picture of the moon surrounded by stars. Children in the conflict condition were instructed to say day to the moon card and night to the sun card. Children in the control condition were divided into two

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groups and instructed to say day or night to either a checkerboard or ribbon card. At every age, accuracy scores were significantly lower for conflict relative to control trials. Other efforts have been made with Stroop-like tasks (Jerger, Martin, & Piozzolo, 1988) and with the Wisconsin card sort task (Zelazo, Reznick, & Pinon, 1995) to study children as young as 31 months; little evidence of successful inhibitory control below 3 years has been found.

We believe that children as young as 18 months might be undergoing development in frontal midline areas that would allow the limited conflict resolution related to eye position to become more general. We had found that children at 18 months could show context-sensitive learning of sequences (Clohessy, Posner, & Rothbart, in press). This is a form of learning that, in adults, appears to require access to the kind of higher level attention needed to resolve conflict. Adults can learn sequences of spatial locations implicitly when each location is invariably associated with another location (e.g., locations 13241324). This occurs even when the adult is distracted with a secondary task known to occupy focal attention (Curran & Keele, 1993). The implicit form of skill learning seems to rely mainly upon subcortical structures. However, when distraction is present, adults are not able to learn context-sensitive sequences (e.g., locations 123213) in which each association is ambiguous. We found that infants as young as 4 months could learn the unambiguous associations, but not until 18 months did they begin to show the ability to learn ambiguous or context-sensitive associations (e.g., locations 1213). Individual children showed wide differences in their learning abilities, and we found that the ability to learn context-sensitive cues was positively related to the caregiver's report of the child's vocabulary development.

According to the analysis of the last section, a more direct measure of the development of executive attention might be reflected in the ability to resolve conflict between simultaneous stimulus events as in the Stroop effect. Since children of this age do not read, we reasoned that the use of basic visual dimensions of location and identity might be the most appropriate way to study the early resolution of conflict.

The variant of the Stroop effect we designed to be appropriate for ages as young as 2–3 years involved presenting a picture depicting a simple object on one side of a screen directly in front of the child and requiring the child to respond with a key that matched the stimulus they were shown (Gerardi–Caulton, in press). The appropriate key could be either on the side of the stimulus (compatible trial) or on the side opposite the stimulus (incompatible trial). The child's prepotent response was to press the key on the side of the target irrespective of its identity. However, the task required the child to inhibit the prepotent response and to respond instead based on identity. The ability to resolve this conflict is measured by the accuracy and speed of their key-press responses.

Results of the study strongly suggested that executive attention undergoes dramatic change during the 3rd year of life. Performance by toddlers at the very beginning of this period was dominated by a tendency to repeat the previous response. Perseveration is associated with frontal dysfunction, and this finding is consistent with the idea that executive attention is still very immature at 24 months. Even at this young age, however, toddlers were already showing a significant accuracy difference favoring compatible over incompatible trials. By the second half of the 3rd and beginning of the 4th year, children showed a strikingly different pattern of responses. Children now performed with high accuracy for both compatible and incompatible conditions, showing the expected slowing for incompatible relative to compatible trials. The developmental transition appeared to occur at about 30 months.

It was also possible to examine the relationship of our laboratory measures of conflict resolution to children's performance on a battery of tasks requiring the child to exercise inhibitory control over their behavior. We found substantial correlations between these two measures. Even more impressive, elements of the laboratory task were significantly related to aspects of temperamental effortful

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control and negative affect. Children who were less slowed by conflict were described as showing lower negative affect. As we have seen, cingulate activity would be expected to relate well at this age to control of distress. It appears that the cognitive measure of conflict resolution has a substantial relation to the aspects of the child's self-control that parents can report.

Individuality

Temperament refers to individual differences in motor and emotional reactivity and self-regulation (Rothbart & Bates, 1998). The temperamental variable related to the development of executive attention is called effortful control, representing the ability to inhibit a dominant response in order to perform a subdominant response. The construct of effortful control is extremely important in understanding the influence of temperament on behavior. Until recently, almost all of the major theories of temperament have focused on temperament's more reactive aspects related to positive and negative affect, reward, punishment, and arousal to stimulation. Individuals were seen to be at the mercy of their dispositions to approach or avoid a situation or stimulus, given reward or punishment cues. More extraverted individuals were expected to be sensitive to reward and to show tendencies to rapid approach; more fearful or introverted individuals, sensitive to punishment, were expected to show inhibition or withdrawal from excitement (Gray, 1987).

Systems of effortful control, however, allow the approach of situations in the face of immediate cues for punishment, and avoidance of situations in the face of immediate cues for reward. The programming of this effortful control is critical to socialization. The work of Kochanska (1995) indicates that the development of conscience is related to temperamental individual differences in effortful control. Kochanska and colleagues found significant prediction from infants' 9-month sustained attention to their contemporaneous restraint in touching a prohibited toy and to a multitask behavioral battery assessing effortful control at 22 months (Kochanska, Tjebkes, & Forman, 1998; Kochanska, Murray, & Harlan, 1999). In two large longitudinal studies (32–66 months and 9–45 months), Kochanska and her colleagues assessed children's effortful control in a laboratory test battery (Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996; Kochanska, Murray, & Coy, 1997; Kochanska et al., 1999). Although the number and difficulty of tasks was varied to assure developmental appropriateness, beginning at age 30 months, children's performance was highly consistent across tasks, suggesting that they all measured a common process that developed over time. Children were also remarkably stable in their performance across time, with the stability of a composite measure of effortful control approaching that of some of the most enduring of traits such as intelligence or aggression. In addition, children's performance and their parents' reports about their temperamental effortful control capacities in their daily lives also converged significantly. Other research suggests longer term stability of executive attention during childhood. In Mischel's work, for example, the number of seconds delayed by preschool children while waiting for physically present rewards predicted their parent-reported attentiveness, ability to concentrate, and control over negative affect when the children were adolescents (Mischel, 1983; Shoda, Mischel & Peake, 1990).

Although temperament researchers had originally believed that temperament systems would be in place very early in development and change little over time (e.g., Buss & Plomin, 1975), we have since learned that temperament systems follow a developmental course (Rothbart, 1989; Rothbart & Bates, 1998). Children's reactive tendencies to experience and express negative and positive emotions and their responsitivity to events in the environment can be observed very early in life, but children's self-regulatory executive attention develops relatively late and continues to develop throughout the early school years. Because executive attention is involved in the regulation of emotions, some children will be lacking in controls of emotion and action that other children can demonstrate with ease.

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Questionnaire studies of 6- to 7-year-olds have found a broad effortful control factor to be defined in terms of scales measuring attentional focusing, inhibitory control, low intensity pleasure, and perceptual sensitivity (Rothbart, Ahadi, Hershey, & Fisher, 1997). Effortful control scores are negatively related to children's scores on a negative affectivity factor. This negative relation is in keeping with the notion that attentional skill may help attenuate negative affect. An interesting example involves the negative relation between effortful control and aggression. Aggression relates negatively to effortful control and positively to surgency and negative affectivity, especially anger (Rothbart, Ahadi, & Hershey, 1994). Since effortful control makes no unique contribution to aggression, it may regulate aggression indirectly by controlling reactive tendencies underlying surgency and negative affectivity. For example, children high in effortful control may be able to direct attention away from the rewarding aspects of aggression, or to decrease the influence of negative affectivity by shifting attention away from the negative cues related to anger. Eisenberg and her colleagues, for example, 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).

Empathy is also strongly related to effortful control, with children high in effortful control showing greater empathy (Rothbart et al., 1994). In a study of elderly hospital volunteers, Eisenberg and Okun (1996) found attentional control to be positively related to sympathy and perspective taking, and negatively related to personal distress. In contrast, negative emotional intensity was positively related to sympathy and personal distress. Effortful control may support empathy by allowing the individual to attend to the thoughts and feelings of another without becoming overwhelmed by their own distress. Similarly, guilt or shame in 6- to 7-year-olds is positively related to effortful control and negative affectivity (Rothbart et al., 1994). Negative affectivity may contribute to guilt by providing the individual with strong internal cues of discomfort, thereby increasing the probability that the cause of these feelings is attributed to an internal rather than external cause (Dienstbier, 1984). Effortful control may contribute further by allowing the flexibility needed to relate these negative feelings of responsibility to one's own specific actions and to negative consequences for another person (Derryberry & Reed, 1994, 1996).

Consistent with these influences on empathy and guilt, effortful control also appears to play a role in the development of conscience. The internalization of moral principles appears to be facilitated in fearful preschool-aged children, especially when their mothers use gentle discipline (Kochanska, 1991, 1995). In addition, internalized control is facilitated in children high in effortful control (Kochanska et al., 1996). Here, we see the influence of two separable control systems, one reactive (fear) and one self-regulative (effortful control), regulating the development of conscience. While fear may provide reactive inhibition and strong negative affect for association with moral principles, effortful control provides the attentional flexibility needed to link negative affect, action outcomes, and moral principles.

These findings illustrate the importance of temperament in general and effortful control in particular to the child's emotional, cognitive, and social development. These underlying temperament systems may also serve a central role in the self-organization of personality (Rothbart, Ahadi, & Evans, 2000). This is particularly evident in the functions of attention, which select and coordinate the most important information and contribute to the storage of this information in memory. While much theorizing emphasizes children's behavior and influences of the immediate environment, children think about their experiences and can use attention to "replay" their positive and negative experiences.

We now revisit Table 1 in its relation to temperament and effortful control. Voluntary attention shifting may moderate the experience of negative affect (row 1), whereas involuntary orientation to negative affect may limit attentional capacity. Further, automatic emotional priming (row 2) may influence the

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meaning of events to the child. Emotional reactivity will also be influential in developing a system of learning that allows us to interact well with others (row 4) and to learn more arbitrary rules connected with conscience (row 5). Finally, development of the attentional systems themselves will provide the capacities underlying the development of self-regulation (row 6). Across development, one would expect emotional and attentional processes to function together to progressively stabilize particular kinds of information, shaping the child's representation of the self and world (Derryberry & Reed, 1994, 1996; Rothbart et al., 1994). The study of temperamental individual differences thus links effortful control mechanisms to issues of empathy, aggression, and conscience that represent central issues of child socialization, and leads us now to a discussion of development and psychopathology.

Development and Psychopathology

The early part of this century saw the development of psychoanalysis (Freud, 1920). Beginning with the neurology known in his time, Freud uncovered unconscious mechanisms that code our implicit experience and proposed methods to prevent them from controlling the behavior of patients suffering from various forms of pathology. Since that time, advances in neuroscience have changed our ability to link specific brain mechanisms to behavior (Kandel, 1998, 1999). At the same time, progress in psychology has begun to specify the mechanisms whereby individuals regulate their feelings and thoughts. We now recognize that both automatic or unconscious impulses and conscious strategies work to control behavior. Future efforts should help us forge an understanding of these concepts at cellular and genetic levels (Albright, Jessell, Kandel, & Posner, 2000).

The area of development and psychopathology examines the interplay between conscious and unconscious mechanisms in both normal and atypical persons (Cicchetti & Cohen, 1995). This approach to development stresses the diverse pathways by which early temperament is refined through experience (Cicchetti & Tucker, 1994). For example, children high in fear and low in self-evaluation may come to avoid achievement situations resulting in possible feelings of inadequacy, leading to even stronger fear or anxiety and avoidance in response to novel or challenging situations. This developmental progression, however, is not without recourse. Changes in the external or internal environment may lead to improvements in an individual's ability to master developmental changes and thus to redirect a developmental trajectory.

Neuroimaging should allow us an increasing ability to examine control mechanisms of the brain and to understand how their malfunction may form the basis for pathologies. For example, to display empathy to others requires that we interpret their signals of distress or pleasure. Imaging work in normal adults shows that sad faces activate the amygdala. As sadness increases, this activation is accompanied by activity in the anterior cingulate as part of the attention network (Blair, Morris, Frith, Perrett, & Dolan, 1999). It seems likely that the cingulate activity represents the basis for our attention to the distress of others. Psychopaths, for example, fail to show behavioral responses to sad faces and lack empathy to the distress of others. It seems likely that they would show either reduced activity in the amygdala or a loss of cingulate activation or both. If in one person the amygdala shows a strong response to the sadness of others, empathy would emerge quite naturally, but if little or no signal occurs, effortful control as influenced by socialization might still allow successful use of whatever signal was present. This is an example of how we might understand at a biological level the various pathways by which development produces either successful socialization or antisocial pathology.

With the introduction of neuroimaging studies, it became possible to discover which brain areas became active during cognitive tasks. As discussed above, many conflict tasks like the Stroop effect produced activation of the anterior cingulate (Bush et al., 1998). Washburn (1998) showed rhesus monkeys could be trained to perform a version of

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the Stroop effect known in humans to activate the cingulate. The monkeys showed many more errors on incompatible trials than do humans, however, despite many hundreds of trials at the task. It is as though the monkeys have somewhat less capacity for avoiding interference, despite very extensive training.

A recent study was conducted with adults who suffer from attention deficit disorder. They performed conflict trials only slightly less efficiently than normals, but unlike normal controls they showed no evidence of anterior cingulate activation and instead showed greater activity on incompatible trials in the anterior insula (Bush et al., 1999). It is possible that the insula represents a more primitive pathway to output, one allowing for less effortful control (Raichle et al., 1994).

Genetic studies of ADHD families have shown that they possess a mutation that affects the dopamine 4 receptor (LaHoste et al., 1996; Smalley et al., 1998). The dopamine 4 receptor is expressed in layer V of the cingulate. While the anterior cingulate is an ancient structure, there is evidence that it has evolved significantly in primates. Humans and great apes appear to have a cell type found mainly in layer V of the anterior cingulate and the insula, which is not present in other primates (Nimchinsky et al., 1999). It is not known what the function of this cell is, but it appears to be a form of projection cell. There is evidence of development in the connectivity of this cell in childhood (Conel, 1959) and it is known that layer V of the cingulate expresses several dopamine receptors (Lidow, Wang, Cao, & Goldman–Rakic, 1998). While there is as yet no direct evidence of the cellular basis of the cingulate activity found in neuroimaging studies, the importance of this area for emotional and cognitive tasks invites future further exploration of linkage between the cellular architecture of this area and its function in self-regulation.

Another disorder that produces a disruption of attentional control, as well as other emotional and cognitive problems, is schizophrenia. Benes (1999) has reported subtle abnormalities of the anterior cingulate in postmortem analyses of schizophrenic brains. She argues that the problem in schizophrenic brains may be a shift in dopamine regulation from pyramidal to nonpyramidal cells. She has also argued that these changes in the cingulate are related to circuitry involving the amygdala and hippocampus. These effects involve the D2 receptor and are strongest within layer II of the anterior cingulate. However, there are strong connections between layers II and V. The schizophrenia studies thus provide an entry to possible dysregulation of the anterior cingulate at a cellular level in a second abnormality noted for its attentional deficits.

Future Directions

This paper has touched upon a number of areas in which we expect significant progress in the future. These include studies at the genetic, cellular, and synaptic levels, as well as at the neurosystems levels. In our understanding of temperamental individual differences, we also see a number of important directions for the next century. Findings suggest developmentally changing pathways through which early temperament, in conjunction with processes of socialization, can influence the development of social-cognitive processes. Tracing such developmental pathways to adaptive outcomes and to the development of behavior problems and psychopathology will be among several promising directions for future work.

Needed in the future is a more thorough understanding of the processes of temperament and how they develop, including surgency and extraversion, fear, and frustration, as well as attention. Many of these advances will come from affective and cognitive neuroscience, where to date much progress has been made in understanding the emotions (Davis, 1992; LeDoux, 1996; Panksepp, 1998) and attention (Posner & Raichle, 1994), as we have discussed in this paper. We expect progress in the study of brain structure and its underlying molecular genetics to be of great future importance.

In addition, we will be looking toward improved temperament assessment methods that target multiple levels: behavior in laboratory paradigms, including marker tasks for the development of brain structures; behavior in nat-

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uralistic daily contexts; physiological measures; informant reports; and self-reports, including information about felt experience. Advances in assessment and empirical understanding will further allow us to link the past and future in the study of development. We envision moving toward bridging research on temperament in childhood with that on personality in adulthood (Caspi, 1998) within a coherent framework on individual differences that temperament can provide.

The pathways between early temperament and future personality outcomes will, of necessity, be intricate, because child individuality unfolds in the context of social relationships, and continuity and change cannot be understood without considering the developmentally changing impact of social experience. To understand developmental pathways, we will need to disentangle complex interaction effects among early temperament predispositions, socialization processes, relationships, and culture. Recent research has begun to provide compelling support for such interactions (Bates, Pettit, Dodge, & Ridge, 1998; Belsky, 1997a, 1997b; Belsky, Hsieh, & Crnic, 1998; Kochanska, 1991, 1995, 1997; Nachmias, Gunnar, Mangelsdorf, Parritz, & Buss, 1996; Wachs & Gandour, 1983).

Because of those complexities, we are likely to find examples of both equifinality and multifinality in development (Cicchetti, 1993). Temperamentally different children may arrive at similar or equivalent outcomes via different pathways. For example, in Kochanska's (1995) studies, fearful toddlers whose parents used gentle discipline and fearless toddlers whose parents capitalized on positive motivation in a close relationship attained comparable levels of conscience. Temperamentally similar children's developmental pathways may also diverge as a result of different effective experiences in relationships or varying cultural pressures (Rothbart, Ahadi, & Evans, 2000).

Finally, in considering issues of developmental pathways, it remains the challenge of this new century, as it has for all previous periods of human history, to seek to balance the needs of the developing child in expressing their individuality with the needs of the society to regulate such expression. Whether by drugs, training, or social engineering, we can be sure that the struggle to control impulses will continue both within and among individuals.

The case of attention deficit disorder is one interesting example. Empirical evidence favors the efficacy of drugs, which, like Ritalin, will provide many children with the help they need to attend to their school lessons (Swanson, Sergeant, Taylor, Sonuga–Barke, Jensen, & Cantwell, 1998). However, it may also be possible that training of high-level attention during the periods when it is undergoing development would prevent the expression of the disorder, at least in some children. The use of drugs and training also does not rule out the idea that the social environment may itself be a serious cause of some pathology. Panksepp (1998), for example, suggests the importance of engineering the social environment of schools to provide access to play with peers that he feels is lacking in the current scene. His suggestion need not conflict with drug treatment and training, and, indeed, multiple avenues for change may be needed to provide the kind of human beings best able to thrive in the society we will have in the future.

As students of normal and pathological development, we must continue attempts to understand the mechanisms involved in self-regulation so that we will have methods to help adapt our children to a changing environment. As members of society, we must try to use our knowledge in a way that enhances the number of children for whom a successful balance between self-expression and the demands of society can be found.

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