

The Neural Correlates of Cognitive Control and the Development of Social Behavior

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23.1 THE DEVELOPMENT OF COGNITIVE CONTROL AND ITS NEURAL BASIS

With development, children and adolescents improve in their ability to control their thoughts, behavior, and impulses and create long-term goals while ignoring distracting information (Casey et al., 2005; Diamond, 2002; Zelazo, 2004). This ability has been termed *cognitive control* or *executive function* (EF) (Bunge and Crone, 2009). According to Bunge and Crone (2009), cognitive control is not a single mechanism, but rather includes several specific functions. This chapter focuses on two of these specific functions. The first function is inhibitory control, or the ability to inhibit dominant responses in favor of more appropriate responses (Rothbart et al., 2003). The second function includes two processes thought to reflect self-monitoring: conflict monitoring, which is indicative of interference and interactions between different information processing pathways (Braver et al., 2001), and error/feedback monitoring, or updating a response

based on feedback and error detection (Bunge and Crone, 2009).

The chapter examines these cognitive control functions and their relation to the development of social behavior. First, the development of cognitive control and its neural correlates is reviewed, focusing on the specific functions of inhibitory control and self-monitoring (including conflict and error monitoring). Then, individual differences associated with the development of these functions and their neural correlates are reviewed. Specifically, the relationship between temperament and inhibitory control/self-monitoring is examined. Temperament refers to stable behavioral and psychological profiles in infancy that shape patterns of behavior across contexts early in development (Kagan, 2001). It is important to examine how intrinsic factors, such as cognitive control processes, are related to temperament because they may influence developmental outcomes. Data suggesting cross-cultural variations in these abilities also are presented. Finally, the role of these functions in the

neurodevelopment of decision making and motivation, including moral and social decisions, as well as moral behavior, is reviewed. This chapter focuses mostly on childhood and adolescence because the neural correlates of cognitive control develop markedly during this period.

23.1.1 Inhibitory Control

Inhibitory control, as defined earlier, is the ability to inhibit a dominant response in favor of a more appropriate response (Rothbart et al., 2003). This function includes the ability to restrain a prepotent response or choosing an alternative response pattern. It has a well-characterized developmental course, with improvements in children's ability to inhibit prepotent responses detected during toddlerhood (Gerardi-Caulton, 2000) and improvements in inhibitory control occurring during the preschool years (e.g., Gerstadt et al., 1994; Rueda et al., 2004; Zelazo, 2006), with marked improvements in inhibitory control continuing during middle childhood (e.g., Simonds et al., 2007) and adolescence (e.g., Anderson, 2002; Huizinga et al., 2006).

Research has pointed to several changes that occur with development in neural activation during inhibitory control tasks. For example, several studies have indicated that activation in the prefrontal cortex (PFC) becomes more focal with age (e.g., Bunge et al., 2002; Durston et al., 2006; Luna et al., 2001). These studies show that activation in certain brain regions increases with age while, at the same time, activation in other brain regions decreases. For example, in a study examining inhibitory control (Durston et al., 2006), decreased activation with development was found in prefrontal regions that were not relevant for task performance. However, an increase in activation, which was associated with improved task performance, was found in the ventrolateral PFC (VLPFC).

In a study examining developmental changes in inhibitory control, Bunge et al. (2002) administered to children between the ages of 8 and 12, as well as adults, a task that combined elements of the go/no-go (response inhibition) and the flanker (interference suppression) paradigms. In a typical go/no-go paradigm, participants are asked to respond to the majority of trials (go trials) and to withhold their response on a minority of the trials (no-go trials). In a typical flanker paradigm, participants are asked to respond on the basis of a central stimulus while ignoring flanking stimuli (flankers). In the task administered by Bunge et al. (2002), participants were asked to press a left button when a central arrow pointed to the left and press a right button when it pointed to the right. The flanker stimuli were congruent with the central target (go trials), incongruent with the target

(go trials), or Xs, in which case participants were asked to refrain from responding (no-go trials).

The findings indicated that for both interference suppression (flanker) and response inhibition (go/no-go), children failed to engage a region in the right VLPFC that young adults recruited (Bunge et al., 2002). The findings also revealed decreased activation with age in the left VLPFC for interference suppression (flanker) and in the parietal and temporal cortices for response inhibition (go/no-go). According to Bunge et al. (2002), these data show that for different types of inhibitory control, children recruit different brain regions to adults. Specifically, children in this study failed to recruit a region in the right VLPFC, which was most robustly activated by both tasks in adults. This can be a result of immature brain structures in children or due to a shift in cognitive strategy between childhood and adulthood (Bunge et al., 2002).

Patterns of increasing and decreasing activation with development have been observed in other studies using the go/no-go paradigm. For example, Tamm et al. (2002) found age-related decreases in activation in the superior and middle frontal gyri as well as increased activation in the left inferior frontal gyrus between ages 8 and 20. In a study by Rubia et al. (2006), functional brain activation was compared between adolescents and adults during three different executive tasks measuring inhibitory control (go/no-go), cognitive interference inhibition (Simon task, also called the directional or motor Stroop task, in which participants are presented with congruent and incongruent stimuli on either side of a computer screen indicating a left or right button press), and attentional set shifting (switch task, during which interference from a previous stimulus-response association has to be inhibited). In all three tasks, adults recruited portions of the PFC, the anterior cingulate cortex (ACC), and the striatum more strongly than adolescents. Additionally, adults engaged the inferior parietal cortex more strongly than adolescents on the Simon and switch tasks, a finding similar to that reported for the go/no-go task by Bunge et al. (2002).

Additional evidence for focalization comes from a study by Luna et al. (2001), who administered an antisaccade task to children (7–12 years), adolescents (13–17 years), and young adults (18–22 years). This task requires participants to suppress looking at a visual target that appears suddenly in the peripheral visual field and instead look away from the target in the opposite direction. The findings indicate that, with age, activation decreased in the superior middle gyrus but increased in the striatum, intraparietal sulcus, frontal eye field, and lateral cerebellum. Additionally, activation in the dorsolateral PFC (DLPFC) was greatest for adolescents as compared with children and young adults.

In a functional magnetic resonance imaging (fMRI) study using the Stroop task (a classic task tapping inhibitory control), [Adleman et al. \(2002\)](#) studied children (ages 7–11 years), adolescents (ages 12–16 years), and young adults (ages 18–22 years). In this task, participants are asked to name the color of ink in which a color word is displayed. [Adleman et al. \(2002\)](#) found that young adults showed increased activation compared to adolescents in the left frontal gyrus. Additionally, young adults showed greater activation than children in the ACC and left parietal and parietooccipital regions as well as in the left frontal gyrus. Compared to children, adolescents showed greater activation in the parietal cortex. Adult and adolescent groups, however, did not differ in activation for this region. These findings suggest that when performing the Stroop task, young subjects are able to recruit parietal structures while PFC function contributing to performance on this task continues to develop into young adulthood. These age-related increases in activation occurred in conjunction with improvements in behavioral performance. These findings suggest that with development, resource recruitment becomes more focal.

Electrophysiological studies have pointed to increased cortical efficiency with age during tasks that require inhibitory control ([Lewis et al., 2006](#)). For example, [Lewis et al. \(2006\)](#) used dense-array electroencephalography (EEG) to measure event-related potentials (ERPs) as children and adolescents performed a go/no-go task. The N2 component of the ERP, an index of inhibitory control, was found to decrease in amplitude and latency with age. Additionally, source modeling of the N2 indicated a developmental decline in posterior midline activity, which was paralleled by increasing activity in frontal midline regions suggestive of the ACC. This pattern of frontalization is in line with other studies that observed reliance on more anterior regions of PFC with improvement of cognitive control (e.g., [Lamm et al., 2006](#); [Rubia et al., 2000](#)). For example, [Lamm et al. \(2006\)](#) found that the N2 in a go/no-go task was source-localized to the cingulate cortex and orbitofrontal cortex (OFC). However, the source of the N2 in older children and in children who showed improved inhibitory control (regardless of age) was estimated to be in the ACC compared to younger children and children who performed poorly, whose N2 source was estimated in the posterior cingulate cortex.

In sum, research examining the neural correlates of the development of inhibitory control suggests that, with age, improvements in this ability are associated with increased focalization and efficiency in recruitment of the PFC. Thus, with development, brain regions that are not relevant for task performance decrease in their activation, while regions relevant for the task increase in their activation. This focalization of the PFC has been

consistently found with various tasks that tap inhibitory control, including flanker, go/no-go, and Stroop tasks.

These changes in functional activation of inhibitory control that occur with development may reflect disengagement from immature neural circuits used by children and adolescents and recruitment of more mature alternative neural networks. However, the differences in activation patterns between children and adults may also reflect children's reliance on different cognitive strategies compared with adults. It is also possible that children engage in ongoing strategy-learning processes or differ from adults in their efforts to complete the task ([Ernst and Mueller, 2008](#)).

23.1.2 Self-Monitoring: Conflict and Error Monitoring

Self-monitoring is often measured through cognitive tasks (e.g., Stroop, flanker, and go/no-go paradigms) by examining response times on trials following an error as compared to response times following correct trials. If inaccurate performance is particularly salient to an individual, more controlled and slower responding in the trial following an error is typically exhibited ([Davies et al., 2004](#); [Luu et al., 2000](#)). This form of self-monitoring can be viewed as a compensatory strategy where subjects slow their reaction time (RT) after an error in order to maximize accurate performance on the upcoming trial.

Studies have examined whether children, after making an error, respond more slowly on subsequent trials. [Backen Jones et al. \(2003\)](#) found that as 3- to 4-year-old children's performance on a Simon Says-type task improved, they tended to show posterror slowing. Using a more fast-paced task-switching paradigm, however, [Davidson et al. \(2006\)](#) failed to find evidence of posterror slowing in 4- to 5-year-old children. Typically, younger children make more errors than adults and may be less aware of them. Some studies have shown that children are able to detect errors, but are unable to correct them. For example, [Bullock and Lutkenhaus \(1984\)](#) found that 18- and 24-month-old children could distinguish between correctly and incorrectly built towers, even when they themselves failed to build the towers correctly. In a study designed to examine this question with preschool children, [Jacques et al. \(1999\)](#) presented 3-year-old children with the dimensional change card sort, in which children are shown two target cards (e.g., a blue rabbit and a red boat) and are asked to sort a series of test cards (e.g., red rabbits and blue boats) first according to one dimension (e.g., color) and then according to the other (e.g., shape). Most 3-year-olds persevere during the postswitch phase, continuing to sort test cards by the first dimension (e.g., [Zelazo et al., 2003](#)). In order to

assess error detection, Jacques et al. (1999) asked children to evaluate the sorting of a puppet. When 3-year-olds watched the puppet persevere, they judged the puppet to be correct. When they saw the puppet sort correctly, they judged the puppet to be wrong, which suggests that 3-year-olds' perseverating performance and error detection are closely linked in this task.

Behavioral measures used to study self-monitoring can also be supplemented with psychophysiological methods to obtain a more comprehensive picture of ACC and PFC involvement in monitoring processes. A good deal of work studying these functions has focused on an error-related potential known as the error-related negativity (ERN). The ERN is a specific neural activity pattern associated with cognitive monitoring that is produced after the commission of an error and has a centromedial scalp distribution (Falkenstein et al., 1991; Gehring et al., 1993; van Veen and Carter, 2002). It is usually observed between 50 and 150 ms postresponse when participants make errors (Falkenstein et al., 1991; Scheffers et al., 1996). Due to its localization and involvement with monitoring, the ERN is seen as part of a neural system that interacts with the PFC to contribute to more efficient cognitive processing (Luu and Tucker, 2001; van Veen and Carter, 2002). The ERN is followed by a positive deflection (Pe) peaking between 200 and 500 ms after the ERN (Davies et al., 2004) and has been associated with awareness of an error (Nieuwenhuis et al., 2001). Source localization models have indicated a generator for the ERN in ACC (e.g., van Veen and Carter, 2002).

Although debate remains as to whether the ERN is a result of error detection (Falkenstein et al., 1991; Gehring et al., 1993) or response conflict processes (Carter et al., 1998; Gehring and Fencsik, 2001), it is generally hypothesized that the ERN is part of a larger performance monitoring system that is influential in the development of self-regulatory skills. As such, the ERN is suggested to serve as a feedforward control mechanism by which self-monitoring can influence future cognitive strategies and overall behavioral performance (Rodriguez-Fornells et al., 2002).

Davies et al. (2004) examined error detection in children using a flanker task and found smaller (i.e., more positive) ERN amplitudes for 7- to 8-year-old children as compared to adolescents. Although ERN amplitudes increase slowly with age, these young children showed behavioral evidence of error detection because, as found in adults, their responses slowed down following an erroneous response. Furthermore, even the youngest children in the study showed evidence of the Pe component, further demonstrating error detection (Davies et al., 2004).

Another type of self-monitoring is known as *conflict monitoring*. As mentioned above, conflict monitoring can be defined as interference and interactions between different information processing pathways (Braver et al.,

2001). Conflict monitoring includes the ability to identify discrepancies in self-performance, and some consider error monitoring as detection of postresponse conflict as opposed to prerespone conflict. Indeed, research has shown an overlap in brain regions associated with both conflict and error monitoring (Ridderinkhof et al., 2004). Conflict monitoring has been found to have a neural basis in ACC. Studies have shown activation in this region for both the conflict elicited by the external environment and that elicited by the individual's own behavior or thoughts (e.g., Carter and van Veen, 2007; Casey et al., 1997a; Posner and Fan, 2004). Once conflict has been detected, the ACC signals for the recruitment of higher-order cognitive processes associated with PFC activation in order to alleviate this conflict (Kerns et al., 2004).

While the majority of neuroimaging work demonstrating ACC activation during conflict monitoring has been found with adults, research shows that this structure also underlies conflict monitoring in children and adolescents (Rubia et al., 2007). For example, in a neuroimaging study with 5- to 16-year-old children, performance on a visual discrimination task that required attention to conflict was positively correlated with the size of a child's right ACC (Casey et al., 1997a). Additionally, in a study with 7- to 12-year-old children, behavioral performance on a go/no-go task was correlated with the degree of ACC activation (Casey et al., 1997b).

In sum, review of studies examining self-monitoring and its neural correlates in children suggests that even young children are capable of self-monitoring, as reflected in error and conflict monitoring. Behaviorally, children have been found to be capable of detecting errors in simple tasks, but incapable of correcting them or identifying them in more complex situations. In addition, for certain tasks, children slow down their responses following an error. Although evidence has been found for self-monitoring in children, this function continues to develop with age as evidenced by increasing ERN amplitude. Thus, the research reviewed suggests that, to a certain degree, children recruit similar neural functions associated with self-monitoring as adults. Specifically, children have been found to recruit the ACC, which has been associated with both error and conflict monitoring.

23.2 INDIVIDUAL DIFFERENCES IN COGNITIVE CONTROL

23.2.1 The Role of Temperament in Cognitive Control

Individual differences in the development of cognitive control have been reported (e.g., Gehring et al., 2000; Henderson, 2010; Lewis et al., 2006; McDermott

et al., 2009; Stieben et al., 2007; White et al., 2011) and have been linked to social outcomes in children. For example, behavioral and physiological measures of cognitive control have been linked to negative mood induction conditions (Lewis et al., 2006, 2007) and to heightened levels of trait anxiety and internalizing symptoms (e.g., Gehring et al., 2000; Stieben et al., 2007). Differences among individuals in cognitive control have also been associated with different types of temperament. For example, a number of studies from different laboratories have found that specific cognitive control functions moderate the developmental trajectory of behavioral inhibition (BI) in children (Henderson, 2010; Thorell et al., 2004; White et al., 2011). BI is a temperament identified early in childhood that predicts heightened emotional reactivity throughout childhood (Fox et al., 2005) and increased risk for anxiety in adolescence (Chronis-Tuscano et al., 2009).

For example, Thorell et al. (2004) examined how BI and inhibitory control assessed at 5 years of age were associated with socioemotional functioning at 9 years of age. The results indicated that behaviorally inhibited children with high levels of inhibitory control were reported as being more socially anxious than behaviorally inhibited children with low levels of inhibitory control. Similarly, Fox and Henderson (2000) found that behaviorally inhibited 4-year-olds with high inhibitory control were less socially competent and more socially withdrawn than behaviorally inhibited children with low inhibitory control.

These findings about the role of inhibitory control for temperamental BI are the opposite of results regarding another EF, attention shifting (Eisenberg et al., 1998). For example, Eisenberg et al. (1998) found that children low on attention shifting and high on parental reports of negative emotions, such as fear, sadness, and anxiety, were rated by their parents and teachers as more shy 2 years later.

White et al. (2011) examined how attention shifting and inhibitory control, which were tested at 48 months of age, moderated the association between BI assessed at 24 months of age and anxiety problems in the preschool years. The results indicated that high levels of inhibitory control increased the risk for anxiety disorders among behaviorally inhibited children whereas high levels of attention shifting decreased the risk for anxiety problems in these children.

In a different study, Lahat et al. (2012a) examined how these two EFs – attention shifting and inhibitory control – moderated the relation between exuberant temperament in infancy and propensity for risk taking in childhood. Temperamental exuberance has been defined by positive reactivity to novelty, approach behavior, and sociability (Putnam and Stifter, 2005). Children with an exuberant temperament are also characterized by impulsivity, sensitivity to reward, fearlessness, and risk

taking (Fox et al., 2001; Polak-Toste and Gunnar, 2006; Rothbart and Bates, 2006). EF was assessed at 48 months of age. Risk-taking propensity was measured when children were 60 months of age. The results indicated that exuberance was positively associated with risk-taking propensity among children relatively low in attention shifting but unrelated for children high in attention shifting. Inhibitory control did not significantly moderate the link between exuberance and risk-taking. Taken together, the findings from these sets of studies on temperament and different types of EF demonstrate that attention shifting and inhibitory control have differential influences on levels of risk or adaptation. Furthermore, these two studies (Lahat et al., 2012a; White et al., 2011) suggest that high levels of attention shifting may serve as a protective factor in the link between temperament and negative outcomes. This conclusion may have important implications for prevention and intervention efforts in the form of training in order to improve attention-shifting skills.

McDermott et al. (2009) provided neurophysiological evidence for the role of cognitive control among individuals with different temperaments. These authors studied adolescents who were part of a larger longitudinal study and were assessed during infancy and early childhood for BI. These adolescents were administered a flanker task, during which ERPs were recorded. The study focused on the ERN component, which is a negative deflection in the ERP waveform produced after the commission of an error. The ERN was found to be larger for adolescents with high childhood BI than for adolescents low on childhood BI. This finding suggests increased error monitoring among highly behaviorally inhibited individuals. In addition, adolescents and their parents completed semistructured diagnostic interviews to assess lifetime presence or absence of anxiety disorders. The results indicated that the ERN moderated the relation between early BI and later anxiety disorders such that, for the participants high on BI, larger ERNs were related to a higher risk of anxiety disorders (McDermott et al., 2009).

In a recent study using dense-array ERPs and source analyses, Lamm et al. (2012) showed that, during an inhibitory control task, children high in temperamental fearfulness showed modeled source activation in areas suggestive of VLPFC across both emotional and nonemotional conditions of the task. However, children low in temperamental fearfulness only showed this pattern of activation during the emotional condition. Results from this study suggest that while children low in temperamental fearfulness recruited increased inhibitory control only during the emotional conditions, or those conditions in which more cognitive control recourses were likely needed, children with high fearful temperaments sustain this increased level of inhibitory control across both neutral and emotional contexts (Lamm et al., 2012). These

findings suggest that temperamentally fearful individuals show increased vigilance not only in emotional situations but also in nonemotional ones. Thus, these fearful individuals may refrain even from social situations that do not induce negative emotions.

Other neurophysiological evidence for the moderating role of inhibitory control has been found for the association between shyness and social-emotional maladjustment (Henderson, 2010). Henderson (2010) examined the associations between shyness, N2 component of ERP, and social adjustment in 9- to 13-year-old children. Participants were administered a flanker task while ERPs were being recorded. In addition, they completed questionnaires assessing temperament, social anxiety, attribution style, and self-perceptions. The results indicated that shyness was associated with poor social outcomes primarily among children with relatively large N2 amplitudes. The results point to the role of conflict in shy children's social adjustment (Henderson, 2010).

Individual differences in cognitive control and their association with social and cognitive adjustment have also been studied using the Stroop task. Perez-Edgar and Fox (2003) examined 11-year-old children who were administered an emotional Stroop task in which emotionally charged words substitute the traditional color words. Based on their RT performance on this task, participants were divided into either an interference or a facilitation group. Children in the interference group were slower to respond to either negative or positive words, whereas children in the facilitation group were faster to respond to these words. The two groups were assessed on cognitive, emotional, and social measures collected at ages 4, 7, and 11. The interference group showed greater socioemotional (but not cognitive) maladjustment over time. In a second study, ERPs were collected during this task. The findings reveal that negative words, as compared with positive words, involve ERP components that are considered to tap attentional processes. Additionally, larger positive slow-wave amplitudes were observed for the facilitation group.

In a different study (Warren et al., 2010), using the emotional Stroop during fMRI, participants were also administered the Attachment Script Assessment in which they were asked to generate stories in response to attachment-related word prompts. This measure assesses secure-base-script knowledge or the degree to which an individual is able to generate narratives in a hypothetical situation in which attachment-related threats are recognized and resolved. The findings indicated that individuals with lower levels of secure-base-script knowledge showed increased activity in brain regions associated with emotion regulation, such as the right OFC, as well as activity in regions associated with inhibitory control, such as the left DLPFC, ACC,

and superior frontal gyrus. These findings suggest that insecure attachment is associated with a greater need in inhibitory control in order to attend to task-relevant nonemotional information (Warren et al., 2010).

In sum, studies examining individual differences in cognitive control and their social-emotional outcomes have shown links with negative mood inductions (Lewis et al., 2006) as well as anxiety disorders and other social problems (e.g., Fox and Henderson, 2000; McDermott et al., 2009; White et al., 2011). For example, highly behaviorally inhibited children, who are also high in inhibitory control, have been found to show negative social outcomes as well as increased anxiety disorders. Children with this temperament have also been found to show increased self-monitoring, as reflected by larger ERNs relative to children with low BI (McDermott et al., 2009). Additionally, children with a fearful temperament showed increased VLPFC source activation even in response to nonemotional stimuli (Lamm et al., 2012). Taken together, these studies suggest that high inhibitory control, as well as high self-monitoring, may result in negative social outcomes for children who are shy or have a more fearful temperament.

23.2.2 Cross-cultural Differences in the Development of Cognitive Control

Research on the development of cognitive control has mostly been conducted in Western cultures. However, an emerging body of cross-cultural studies suggests that Asian children may outperform Western children on measures of cognitive control (e.g., Lahat et al., 2010; Sabbagh et al., 2006).

Research comparing children from Western and Asian cultures has shown that Chinese children perform better on behavioral and neurophysiological measures of EFs than North American children (e.g., Chen et al., 1998; Ho, 1994; Lahat et al., 2010; Sabbagh et al., 2006; Wu, 1996). For example, Sabbagh et al. (2006) administered a battery of EF and theory of mind (ToM) tasks to preschoolers from China and the United States. ToM is the ability to attribute mental states – beliefs, intents, and desires – to oneself and others and to recognize that mental representations can differ across individuals (Premack and Woodruff, 1978). The Chinese preschoolers showed better performance than the US preschoolers on all measures of EF, but not on measures of ToM. However, individual differences in EF predicted ToM performance in both groups.

Chinese children's advanced performance on EF tasks may stem from the opportunities to exercise and practice these abilities that they encounter within their culture. For example, Chinese parents expect children to master impulse control at a much younger age than North American parents (Chen et al., 1998; Ho, 1994;

Wu, 1996). Compared with Western parents, Chinese parents are more controlling and protective in child rearing. For example, they often encourage their young children to stay close to and to be dependent on them. Indeed, most Chinese infants and toddlers sleep in the same bed or in the same room as their parents (Chen et al., 1998). In addition, impulse control is more highly valued in Chinese daycare settings than in North American daycare settings (Tobin et al., 1989).

Another possibility for Chinese children's superior cognitive control was suggested by Lahat et al. (2010) in a study that focused on the N2 component of ERP. Cultural differences in the importance that parents place on impulse control could affect children's motivation to succeed on a task such as the go/no-go task, resulting in greater PFC activation. The study compared 5-year-old children from a Chinese-Canadian ethnic background with children from a European-Canadian background on a go/no-go task. No behavioral differences between the two cultural groups were observed, but robust N2 amplitude differences were found. Chinese-Canadian children showed larger (i.e., more negative) N2 amplitudes than European-Canadian children on the right side of the scalp on no-go trials as well as on the left side of the scalp on go trials. Source analyses of the N2 showed greater modeled source activation for Chinese-Canadian children in dorsomedial, ventromedial, and (bilateral) ventrolateral PFC. These findings reveal that Chinese-Canadian children show greater hemispheric differentiation than European-Canadian children, suggesting more advanced cognitive control. Moreover, the asymmetrically lateralized N2 may be a reliable marker of both effortful inhibition (on the right) and effortful approach (on the left).

Behavioral cultural differences were not observed in the Lahat et al. cross-cultural study, despite cultural differences found in other research (e.g., Sabbagh et al., 2006). This discrepancy can stem from the different cognitive control tasks that were used or from the different age groups that were studied. Furthermore, the Chinese-Canadians in the Lahat et al. study grew up in Canada, whereas previous research examined Asian children living in Asia. In any case, this study demonstrates that neurophysiological techniques can provide a measure of neurocognitive function that is more sensitive than behavioral data alone.

In sum, individual differences in cognitive control have also been observed in cross-cultural variations. Specifically, an emerging body of research comparing children from Asian and Western cultures has shown behavioral (e.g., Sabbagh et al., 2006) as well as neurophysiological (Lahat et al., 2010) evidence, suggesting advanced cognitive control abilities among children from a Chinese cultural background compared with children from a Western cultural background. Although the reasons for these differences

are not clear yet, it is possible that differences in socialization between the two cultures play a major role.

23.3 THE ROLE OF COGNITIVE CONTROL IN DECISION MAKING AND MOTIVATION

23.3.1 Motivation-related Decisions

Cognitive control has also been implicated in decision-making processes. Studies with adults support the idea of a frontostriatal network linking cognitive control and motivation during decision making (see Somerville and Casey, 2010). Fewer studies have examined the role of the development of cognitive control as it affects the emergence of decision-making skills.

A simple paradigm that has been used to assess basic decision making with young children is delay of gratification, which measures children's ability to give up an immediate reward in favor of a larger reward later. For example, participants are seated in front of a piece of candy while an experimenter leaves the room. If they wait for the experimenter to return, they get two treats; otherwise they get only one (Mischel et al., 1972). Variations of the standard delay of gratification paradigm have shown developmental differences throughout the preschool years. For example, in one study (Kochanska et al., 1996), children were asked to hold candy in their mouth without eating it until they were told to do so. In a second task, children were asked not to peek while they could hear that the experimenter was wrapping a gift for them. Children's ability to delay gratification increased significantly from 3 to 4 years of age. In a study linking delay of gratification and decision making, Prencipe and Zelazo (2005) examined children's delay of gratification for self and other (the experimenter). Three-year-olds typically chose an immediate reward for themselves and a delayed reward for other (the experimenter). According to Prencipe and Zelazo, these findings suggest that 3-year-olds are capable of adaptive decision making but still have difficulty regulating their own approach behavior in motivationally salient situations. According to these authors, it is possible that their behavior is driven by the relatively automatic processes rather than by more deliberate prefrontal networks. The findings can be explained in light of Barresi and Moore's (1996) model of the development of perspective taking. It is possible that 3-year-olds may have made impulsive choices in the self condition because they took an exclusively first-person perspective on their own behavior and had difficulty adopting a more objective, third-person perspective according to which delay would be preferred. In contrast, 3-year-olds may have chosen delayed rewards in the other condition because they

took an exclusively third-person perspective and had difficulty appreciating the experimenter's subjective perspective (i.e., his or her own desire for immediate gratification).

In more complex situations, individuals are often required to make approach-avoidance decisions in the face of uncertainty. One common measure of complex decision making in adults is the Iowa gambling task (IGT; [Bechara et al., 1994](#)). In this task, participants are asked to choose cards from four decks that contain a different number of cards that could lead to their winning or losing money. During the task, the participants learn that some decks are more advantageous than others. [Kerr and Zelazo \(2004\)](#) modified the IGT to create a version for children that included two decks of cards, one advantageous and one disadvantageous. Feedback on participants' decisions was provided in the form of happy (reward) and sad (loss) faces. Choosing cards from the disadvantageous deck resulted in more rewards on every trial but also with occasional (unpredictable) large losses. Three-year-olds failed to develop a preference for the advantageous deck. However, 4- and 5-year-olds were able to make advantageous decisions ([Kerr and Zelazo, 2004](#)).

Although these studies suggest a steady improvement in cognitive control and decision making with development, according to [Somerville and Casey \(2010\)](#), cognitive control and decision making can often be impaired in light of emotionally charged interactions. This impaired cognitive control is especially pronounced during adolescence when rates of risky behavior, such as drug use and risky sexual conduct, increase ([Casey et al., 2005](#); [Steinberg, 2008](#)). Thus, although adolescents show improvements in cognitive control, their goal-oriented behavior can be diminished in light of motivational cues of potential reward ([Cauffman et al., 2010](#); [Figner et al., 2009](#); [Steinberg et al., 2009](#)). For example, [Figner et al. \(2009\)](#) used a gambling task in which reward feedback was given either during decision making or after decision making. The findings show that adolescents made riskier choices compared to adults, but only in the condition in which the reward was given during the decision. This condition is more emotionally charged and elicits greater arousal.

Another study examined participants between the ages of 10 and 30 years and used a delay discounting task ([Steinberg et al., 2009](#)) in which participants were asked to choose between an immediate reward of less value (e.g., \$400 today) and a variety of delayed rewards of more value (e.g., \$700 1 month from now or \$800 6 months from now). The findings indicate that, before age 16, children showed a greater willingness to accept a smaller reward immediately than a large reward that was delayed. [Cauffman et al. \(2010\)](#) obtained similar results examining the same age range with a modified version of the IGT. Results indicate that approach behaviors

(a tendency to choose from the advantageous decks) display an inverted U-shape relation to age, peaking in mid- to late adolescence. In contrast, avoidance behaviors (a tendency to refrain from choosing from the disadvantageous decks) increase linearly with age, with adults avoiding disadvantageous decks at higher rates than both preadolescents and adolescents. Taken together, these studies show that risky choices tend to peak between 14 and 16 years of age, followed by a decline in risky behavior.

[Casey et al. \(2008\)](#) proposed a model describing the neurocircuitry of the development of control and motivational processes. According to this model, top-down prefrontal regions involved in cognitive control develop linearly with age, whereas bottom-up striatal regions, which are involved in processing of salient cues in the environment, develop in an inverted U-shaped function. Evidence for such a frontostriatal circuitry comes from studies using diffusion tensor imaging and fMRI. Casey and colleagues ([Casey et al., 2007](#); [Liston et al., 2006](#)) have found that the strength of the connection between frontal and striatal regions is associated with effective cognitive control in typically and atypically developing individuals.

fMRI studies examining the role of the striatum in salient and motivational contexts support the idea that adolescents show enhanced sensitivity to incentives relative to children and adults ([Ernst et al., 2005](#); [Galvan et al., 2006](#); [Geier et al., 2010](#); [May et al., 2004](#)). For example, [Ernst et al. \(2005\)](#) used a monetary reward task and found stronger activation among adolescents than adults in the left nucleus accumbens, a structure in the striatum thought to be involved in reward processing. In addition, a reduction in the fMRI blood oxygen level dependent (BOLD) signal in the amygdala in response to reward omission was larger for adults than for adolescents.

Few studies (e.g., [Hardin et al., 2009](#); [Jazbec et al., 2006](#)) have examined the link between cognitive control and motivational processes. Recent research has shown that adolescents' cognitive control can be enhanced in light of incentives. For example, when participants were promised a financial reward for accurate performance on certain trials of an antisaccade task, cognitive control was improved for adolescents more than adults ([Jazbec et al., 2006](#)). This finding has also been obtained with social rewards, such as a happy face ([Kohls et al., 2009](#)). [Geier et al. \(2010\)](#) studied the neural underpinnings of reward processing and its influence on cognitive control in adolescence using a modified version of an antisaccade task. The results indicate that faster correct inhibitory responses were provided on reward trials than on neutral trials by both adolescents and adults. Additionally, fewer inhibitory errors were made by adolescents. For reward trials, the BOLD signal was attenuated in ventral striatum in adolescents during cue assessment.

This was followed by overactivation in adolescents during response preparation (i.e., during fixation after the reward cue) in the ventral striatum, as well as the precentral sulcus, which is important for controlling eye movements. These findings suggest enhanced activation in adolescents in control regions as a result of reward anticipation (Geier et al., 2010).

In sum, studies examining the development of cognitive control in decision making have pointed to an inverted U-shaped trend in development (see Somerville and Casey, 2010). Studies with young children show steady improvements in the ability to delay gratification (e.g., Prencipe and Zelazo, 2005) as well as more effective decision making (e.g., Kerr and Zelazo, 2004). However, studies have shown a greater propensity for risky decisions during adolescence in light of motivationally salient situations (e.g., Cauffman et al., 2010). fMRI studies examining the link between cognitive control processes and motivation have found enhanced activation during adolescence in brain regions associated with cognitive control during anticipation of reward (Geier et al., 2010).

23.3.2 Social and Moral Decisions and Behavior

Evidence for the role of cognitive control in influencing more specific types of decisions, such as social and moral decisions comes from behavioral, fMRI, and ERP studies (e.g., Greene et al., 2001, 2004; Lahat et al., in press, 2012b; Lahat and Zelazo, 2010). In these studies, participants are typically asked to make a decision about whether a social or moral violation is acceptable or unacceptable to perform. Moral violations involve intrinsic negative consequences for others, such as physical harm or issues of fairness (Nucci, 1981; Smetana, 2006; Turiel, 1983).

For example, Greene et al. (2001, 2004) found evidence for the role of cognitive conflict and inhibitory control in the moral judgments of adult participants. These authors distinguish between impersonal moral dilemmas and personal moral dilemmas. An example of an impersonal dilemma is the *trolley* dilemma (Thomson, 1986) in which one has to decide whether to allow an out-of-control trolley to continue down a track where it will kill five people or whether to push a switch diverting it to a track where it will kill only one person. However, in a variation of this dilemma, the *footbridge* dilemma, the only way to save the five people is to push a large person in front of the trolley, killing him but saving the others. This latter dilemma is a personal dilemma as it is introduced in an 'up-close-and-personal manner' (Greene et al., 2001) and the bystander witnessing the event now becomes a moral agent. Most individuals assert that it is acceptable to sacrifice one person in order to save five in the case of the trolley dilemma, but not in the case of the footbridge dilemma (Greene et al.,

2001). Greene et al. (2001) found that RTs were longer when participants judged personal moral violations as acceptable than when they judged personal moral violations as unacceptable. This effect was not found for impersonal moral judgments. According to Greene et al. (2001), personal moral violations elicit a negative social-emotional prepotent response, which results in judging the moral violation as unacceptable. An individual must overcome this prepotent response in order to judge a personal moral violation as acceptable. Thus, according to Greene, making a utilitarian judgment to serve the greater good involves cognitive control in order to overcome prepotent responses elicited by personal dilemmas.

In a different study (Greene et al., 2004), the authors focused on personal moral dilemmas only and explored whether different patterns of neural activity in response to these dilemmas are correlated with differences in moral decision-making behavior. For this purpose, Greene et al. (2004) made a further distinction within the class of personal dilemmas. They differentiated between difficult personal moral dilemmas, which elicit high conflict, and easy personal moral dilemmas, which elicit low conflict. Difficult personal dilemmas are a class of dilemmas that create cognitive and emotional tension compared to easy dilemmas. In response to these dilemmas, participants tend to answer slowly, and they exhibit no consensus in their judgments. An example of a difficult dilemma is the *crying-baby* dilemma in which an individual and other townspeople have sought refuge in a cellar to escape from enemy soldiers who have taken over the village. The protagonist's baby begins to cry loudly, and this could summon the attention of the soldiers, who might kill the protagonist, his child, and the others hiding out in the cellar. To save himself and the others, the protagonist must smother his child to death. This case contrasts with easy, low-conflict, personal moral dilemmas that receive relatively rapid and uniform judgments. One such example is the *infanticide* dilemma, in which a teenage mother must decide whether or not to kill her unwanted newborn infant. The latter dilemma is considered easy in the sense that most participants tend to agree that an unwanted infant should not be killed.

Greene et al. (2004) examined whether different brain regions are involved in judgments of difficult versus easy moral dilemmas. The dilemmas were classified as either difficult or easy according to their RTs, with difficult dilemmas having longer RTs. The findings indicate that judgments of difficult dilemmas, as compared to easy dilemmas, involved increased activity bilaterally in both the DLPFC and the ACC. This contrast also revealed activity in the inferior parietal lobes and the posterior cingulate cortex. Greene et al. (2004) also compared the neural activity associated with utilitarian judgments (judging a personal moral violation as acceptable

in favor of the greater good, such as smothering the baby in the crying-baby dilemma) to that associated with non-utilitarian judgments (prohibiting a personal moral violation despite its utilitarian value, such as allowing the baby to live in the crying-baby dilemma). The authors found increased activity for utilitarian, as compared with nonutilitarian, moral judgments bilaterally in the anterior DLPFC and in the right inferior parietal lobe. In addition, they found increased activity for utilitarian moral judgments in the more anterior region of the posterior cingulate (Greene et al., 2004). These findings show that judgments of difficult dilemmas engage brain areas associated with the detection of conflict and the operation of inhibitory control. According to Greene et al. (2004), when participants respond in a utilitarian manner, such responses reflect not only the involvement of abstract reasoning but also the engagement of cognitive control in order to overcome prepotent social-emotional responses elicited by these dilemmas.

Evidence for the role of cognitive control in moral judgments has been found in children as young as 10 years of age (Lahat et al., 2012b, *in press*; Lahat and Zelazo, 2010). These authors obtained behavioral and neurophysiological data suggesting that the detection of cognitive conflict distinguishes between moral decisions and social conventional decisions. Social conventions are behavioral uniformities that serve to coordinate individuals' interactions in a social system (Nucci, 1981; Smetana, 1981, 2006; Turiel, 1983). These conventions, such as forms of address and modes of greeting, are symbolic elements of social organization. Social conventions, such as eating with one's fingers or wearing pyjamas to school, can vary across different social systems, are contingent on societal rules, and can be altered by authority or social consensus. This is in contrast to moral acts, such as hitting, lying, and stealing, which are considered universal, independent from rules and authority, and unalterable.

In a set of studies, Lahat et al. (2012b, *in press*) measured RTs and focused on the N2 component of ERP, which, as mentioned earlier, has been considered to be an index of cognitive control (e.g., Nieuwenhuis et al., 2003). Adults, children (10 years), and adolescents (12–14 years) were administered a moral-conventional judgments task while ERPs were being recorded and RTs were measured. The task included scenarios describing a social interaction and had three possible endings: a moral violation, a conventional violation, and a neutral act. Participants were to judge whether the act was acceptable or unacceptable to perform in a situation where a social rule was assumed or removed (i.e., "imagine that there is no rule against the act; is it okay or not okay to perform the act?"). The findings revealed that, at all ages, RTs were faster for moral rather than conventional violations when a rule was assumed (Lahat et al., 2012b).

ERP data indicated that adults', but not adolescents', N2 amplitudes were larger (i.e., more negative) for conventional rather than moral violations when a rule was assumed (Lahat and Zelazo, 2010). Taken together, these results suggest that judgments of conventional violations involve increased conflict detection compared to moral violations, and these two domains are processed differently across development. The findings were explained by the idea that judgments of conventional violations are more explicitly dependent on rules, and thus a violation of the rule results in increased conflict detection. However, judgments of moral violations are based more directly on the intrinsic negative consequences of the act and thus less cognitive conflict is detected in these trials. These findings inform theories of moral development and suggest that cognitive processing of moral judgments changes with age.

The role of cognitive control has also been found to be crucial for moral behavior, specifically that of lie-telling behavior in children and adolescents (Evans and Lee, 2011; Evans et al., 2011; Talwar and Lee, 2008). For example, Talwar and Lee (2008) studied children between the ages of 3 and 8 years. In this study, participants were told not to peek at a toy. However, most children could not resist the temptation and peeked and later lied about it. Children's conceptual moral understanding of lies, executive functioning, and theory-of-mind understanding were also assessed. Results indicated that children's initial denials about peeking were related to inhibitory control measured with a Stroop and whisper task (in which children are required to whisper their responses rather than say them aloud). Denials about peeking were also related to moral understanding and first-order false belief understanding; that is, telling a lie successfully required deliberately creating a false belief in the mind of another. Additionally, children's ability to maintain their lies was related to their second-order belief understanding (e.g., Ann knows that Sally thinks her toy is in the box), a finding in line with research showing that second-order beliefs begin to emerge around 6 years of age and undergo steady development well into adolescence (Sullivan et al., 1994). These findings suggest that social and cognitive factors may play an important role in children's lie-telling abilities.

In a similar paradigm, designed for older participants, Evans and Lee (2011) examined 8- to 16-year-old children's tendency to lie, the sophistication of their lies, and related cognitive factors. Participants were left alone and asked not to look at the answers to a test, but the majority of children peeked. The researcher then asked a series of questions to examine whether the participants would lie about their cheating and, if they did lie, evaluate the sophistication of their lies. Additionally, participants completed measures of EF, including inhibitory control measured with a Stroop task. Results revealed

that the sophistication of 8- to 16-year-old children's lies, but not their decision to lie, was significantly related to executive functioning skills and performance on the Stroop task. In these studies, participants with a better performance on the Stroop were better able to conceal incriminating knowledge they ought not to know. According to these authors, the Stroop task is thought to measure both inhibitory control and working memory. In the situation created in these studies, participants were required to hold in working memory their incriminating knowledge in order to create answers different from this knowledge. At the same time, they must inhibit reporting the truth. Taken together, these findings suggest that whether a person is a good liar who is able to, or a bad liar who is not able to, maintain his/her lie, is dependent on working memory in conjunction with inhibitory control.

In a different study (Evans et al., 2011), Chinese preschoolers' ability to tell a strategic lie by making it consistent with the physical evidence of their transgression was investigated. Participants in this study were left alone in a room and asked not to lift a cup to see its contents. If children lifted up the cup, the contents would be spilled and evidence of their transgression would be left behind. Upon returning to the room, the experimenter asked children whether they peeked and how the contents of the cup ended up on the table. The findings revealed that young children were able to tell strategic lies to be consistent with the physical evidence by about 4 or 5 years of age, and this ability increases in sophistication with age. Furthermore, the study revealed that children's theory-of-mind understanding and inhibitory control skills were significantly related to their ability to tell strategic lies in the face of physical evidence. Although this study was conducted in a non-Western culture, no cross-cultural comparison was made and, although research suggests that Chinese children are more advanced than Western children in cognitive control (e.g., Lahat et al., 2010; Sabbagh et al., 2006), it is not known if Chinese children are more advanced at telling strategic lies than Western children.

In sum, studies examining the neural correlates of moral judgments with adults have shown that certain classes of moral dilemmas (i.e., difficult dilemmas) involve inhibitory control and detection of conflict. These studies show increased activation in ACC and DLPFC during judgments of these dilemmas (Greene et al., 2004). The role of cognitive control in moral and social judgments has also been studied with a behavioral/ERP paradigm in children, adolescents, and adults (Lahat et al., 2012b; Lahat and Zelazo, 2010). Findings reveal larger N2 amplitudes for adults, but not children, in response to conventional rather than moral violations. This finding suggests that the morality-convention distinction continues to develop well into early

adolescence. Finally, the role of inhibitory control has also been demonstrated in moral behavior (e.g., Evans and Lee, 2011).

23.4 CHAPTER SUMMARY AND FUTURE DIRECTIONS

In this chapter, the role of cognitive control across different social behaviors was reviewed. The chapter focused on the development of the neural correlates of two specific cognitive control functions: inhibitory control and self-monitoring (including conflict and error monitoring). As described earlier, these specific functions have been found to develop with the maturation of the PFC and patterns of activation increase with age (Zelazo et al., 2008).

Studies examining the neural correlates of the development of inhibitory control have shown that PFC activation not only increases with age, but also becomes more focalized (e.g., Bunge et al., 2002; Durston et al., 2006; Luna et al., 2001). As discussed, with development, brain regions not associated with task performance decrease in activation, while regions relevant to task performance increase in activation. With development, children also show improvements in self-monitoring abilities. For example, they are better able to detect and correct errors (e.g., Backen Jones et al., 2003; Bullock and Lutkenhaus, 1984). These behavioral data are in line with findings from neurophysiological studies, which show an increase in ERN amplitude with age (Davies et al., 2004). An additional form of self-monitoring that has been studied is conflict monitoring. Some argue that error monitoring is a specific type of conflict monitoring, which occurs postresponse and, although these abilities are distinct, there is an overlap in their functional activation, namely the ACC (Ridderinkhof et al., 2004). Even young children have been found to recruit the ACC in tasks that require self-monitoring (Casey et al., 1997a,b).

Inhibitory control and self-monitoring have been found to show associations with individual differences and their social-emotional outcomes (e.g., Fox and Henderson, 2000; Lamm et al., 2012; McDermott et al., 2009; White et al., 2011). This body of research has shown that children with a fearful temperament who are also high in inhibitory control or self-monitoring are at risk of developing negative social-emotional outcomes, such as social withdrawal and anxiety disorders. Evidence on individual differences associated with cognitive control come mostly from behavioral and electrophysiological studies. Future research should examine the association between temperament and cognitive control using neuroimaging in order to better localize differences in brain activation.

Individual differences relating to cultural variations have also been found, particularly when comparing Chinese children with children from Western cultures. These studies provide behavioral (Sabbagh et al., 2006) as well as neurophysiological (Lahat et al., 2010) evidence for advanced performance on cognitive control tasks among Chinese children. It is possible that socialization processes that differ across the two cultures contribute to these differences in cognitive control. The cross-cultural neurophysiological work has been conducted with Asian children who grew up in North America. Future research should compare Western children with Asian children who are raised in Asia. This would provide a more pure cross-cultural comparison.

In this chapter, the role of cognitive control in the development of decision making and motivation was also reviewed. Studies have shown that the development of decision making takes an inverted U-shaped form, with steady improvements during childhood (e.g., Kerr and Zelazo, 2004) and a propensity for risk taking during adolescence (Somerville and Casey, 2010). fMRI studies with adolescents (e.g., Geier et al., 2010) have shown increased activation in brain regions associated with cognitive control during anticipation of reward. Most of the work has focused on monetary or other types of non-social rewards. Future research should examine the relation between cognitive control and social reward, such as social acceptance.

Research has shown that cognitive control also plays a role in the development of moral and social decisions, as well as moral behavior. Specifically, the role of cognitive conflict has been demonstrated in studies with adults, in which increased activation has been found in the ACC and DLPFC (e.g., Greene et al., 2001, 2004). Cognitive conflict has also been found to play a role in adults', but not children's, distinction between moral and conventional judgments, as reflected in N2 amplitudes (Lahat and Zelazo, 2010). Finally, a role for the development of inhibitory control has been identified in children's and adolescents' moral behavior (Evans and Lee, 2011). Future research on the role of cognitive control in the development of moral judgment should examine direct relations between neurophysiological correlates of moral judgments and various types of cognitive control. This would allow to better pinpoint which cognitive control functions are involved in moral development.

SEE ALSO

Diseases: The Developmental Neurobiology of Repetitive Behavior; **Induction and Patterning of the CNS and PNS:** Area Patterning of the Mammalian Cortex; The Formation and Maturation of Neuromuscular

Junctions. Migration: Cell Polarity and Initiation of Migration.

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