THE NEUROBIOLOGY AND DEVELOPMENT OF COGNITIVE AND AFFECTIVE CONTROL

Todd A. HARE, B.J. CASEY[*]

Sackler Institute for Developmental Psychobiology,
Weill Medical College of Cornell University, USA

ABSTRACT

Cognitive control has been described and referred to over the years by different terminology including "controlled processing", "central executive" and "attentional bias". We present behavioral and neuroimaging experimental investigations of this psychological construct reflecting top-down control in overriding inappropriate thoughts, actions, and emotions. The ability to override competing actions and emotions is a key component of cognitive and social functioning and at the core of a child's development. We show in a series of behavioral and imaging studies that the development of frontostriatal and frontoamygdala circuitry may underlie mature cognitive and affective control.

KEY-WORDS: *cognitive control, development, emotion, striatum, prefrontal cortex*

Introduction

The term cognitive control refers to the ability to override competing thoughts and actions in favor of goal directed ones (Desimone & Duncan, 1995; Miller & Cohen, 2001). It has been referred to as "controlled processing", "effort", "central executive", "supervisory attention systems", "attentional bias", "conflict resolution" within cognitive theories (Posner & Boies, 1971; Kahneman, 1973; Posner & Snyder, 1975; Shiffrin & Schneider, 1977; Baddeley, 1986; Allport, 1987; Shallice, 1988; Posner & Petersen, 1990; Cohen & Servan-Schreiber, 1992; Desimone & Duncan, 1995; Braver & Cohen, 2000; Miller & Cohen, 2001). With advances in neuroimaging tools and the recent integration of cognitive and affective neuroscience, the neurobiological basis of this construct and its role in both cognitive and social behavior is beginning to be understood. The current paper

[*] *Corresponding address:*
B.J. Casey, Sackler Institute for Developmental Psychobiology
Weill Medical College of Cornell University, 1300 York Avenue, Box 140,
New York, NY 10021
Email: bjcasey@princeton.edu

presents empirical studies delineating the neural circuitry of cognitive and affective control and its development.

Theories of cognitive development characterize immature cognition as being more susceptible to interference from competing information and actions (Brainerd & Reyna, 1993; Dempster, 1993; Casey, Tottenham, & Fossella, 2002; Morton & Munakata, 2002). Developmental tasks like the classic Piagetian A not B task are used to examine cognitive control in infants (Piaget, 1954; Diamond, 1985), while in older children, this psychological construct is measured by Strooplike tasks (Tipper, Borque, Anderson, & Brehaut, 1989) card sorting tasks (Zelazo, Burack, Benedetto, & Frye, 1996; Munakata & Yerys, 2001) and go-nogo tasks (Luria, 1961; Casey et al., 1997). Across all of these tasks, younger children have more difficulty ignoring irrelevant salient information and actions in favor of adaptive ones (Mischel, 1958; Mischel, 1961; Mischel & Metzner, 1962; Mischel, 1966; Mischel & Underwood, 1974). This ability is further complicated when the information is of an emotional content.

The interaction of cognitive and emotional processes plays an important role in the development of regulatory behavior in children. The term, *emotion regulation*, has been coined to describe this interaction and refers to the dynamic process by which emotions influence other psychological or physiological processes and those processes influence emotions (Campos, Mumme, Kermoian, & Campos, 1994; Cole, Michel, & Teti, 1994; Fox, 1994). Accordingly, this ability relates to the manner in which an emotion, like happiness or sadness, facilitates or interferes with other processes rather than the simple presence of an emotion (Frijda, 1988; Cole et al., 1994; Cole, Martin, & Dennis, 2004). The ability to regulate or override such emotional processes is a component of cognitive control (Derryberry & Rothbart, 1988; Rothbart & Ahadi, 1994; Rothbart, Derryberry, & Posner, 1994; Derryberry & Rothbart, 1997) and is illustrated in delay of gratification (Mischel, 1958; Mischel, 1961; Mischel & Metzner, 1962; Mischel, 1966; Walls & Smith, 1970; Mischel & Underwood, 1974; Toner & Smith, 1977). In this paper, we present recent studies that assess behavioral and neural responses when approaching and avoiding emotional or non-emotional information using functional neuroimaging, specifically functional magnetic resonance imaging (fMRI).[1]

Several studies have used fMRI in children and adults to determine the neural substrates that mediate aspects of cognitive control involved in overriding

---

[1] Functional magnetic resonance imaging (fMRI) is a tool for non-invasively examining changes in patterns of brain activity without exposure to potentially harmful effects of radioactive isotopes. It is sensitive to changes in oxygen levels of the blood in the brain (Kwong et al., 1992; Ogawa et al., 1992) that eliminates the need for exogenous, invasive contrast agents (Turner, Le Bihan, Moonen, Despres, & Frank, 1991). This methodology capitalizes on the magnetic differences between oxygenated and deoxygenated blood. During brain activation, localized increases in blood flow increase blood oxygenation (and consequently reduce deoxygenated hemoglobin), causing detectable changes in the MR signal.

competing actions (see Casey, Galvan, & Hare, in press-a for review). Less is known about the neurobiological development of top-down control of emotion (Monk et al., 2003). We present recent findings from our laboratory on the development and neural substrates of the top-down and bottom-up modulation of behavior and emotions.

Neural substrates underlying the development of cognitive control

The neural substrates implicated in cognitive control include prefrontal related circuitry (Miller & Cohen, 2001; Casey et al. 2002). A core component of cognitive control is the ability to regulate thoughts and actions. This aspect of control is often studied using go/nogo tasks. Typically in these tasks subjects are asked to respond to frequently occurring targets, but to withhold a response to a rare nontarget. Subjects must override the prepotent tendency to respond in order to successfully withhold responses to rare nontarget trials. In our original fMRI study on the development of cognitive control (Casey et al., 1997), we focused on differences between children and adults in the recruitment of prefrontal regions when overriding a response. In this study, activity in the anterior cingulate and ventral prefrontal regions was correlated with the number of errors made during performance of the go/nogo task. Age-wise comparisons showed more diffuse activation of prefrontal cortex in children relative to adults. Specifically, children recruited the dorsolateral prefrontal cortex, an area that did not correlate with task performance, more than adults (Casey et al., 1997; Luna et al., 2001). The more diffuse pattern of prefrontal activation seen in children relative to adults may coincide with fine-tuning of prefrontal regions as relevant connections are strengthened and others are attenuated with maturity (Casey et al., in press-a; Casey, Tottenham, Liston, & Durston, in press-b). Prefrontal connectivity has been associated with both developmental and individual differences in the efficiency of cognitive control (Nagy, Westerberg, Klingberg, 2004; Liston et al., submitted).

Studies that explicitly manipulate the level of cognitive control required to perform a task may provide a better assessment of which prefrontal regions are specific to this function. Findings from a go/nogo paradigm where task difficulty was parametrically manipulated by varying the number of go responses preceding a nogo are consistent with this notion (Durston et al., 2002). Both children and adults made more errors when task difficulty increased. Adults showed a corresponding increase in specific prefrontal and parietal regions for correct nogo responses as the number of preceding go trials increased. However, children appeared to maximally activate the same regions for nogo trials preceded by only one go trial, suggesting that immature cognitive control networks are more susceptible to interference regardless of preceding context.

As these networks become more refined with development, less activation (fine tuned- less relevant regions attenuate) is needed to overcome interference and additional activity is recruited only when necessary in order to overcome highly salient competing responses. Adults also show enhanced activity of frontoposterior

cortical networks during cognitive control tasks (Luna et al., 2001; Bunge, Dudkovic, Thomason, Vaidya, & Gabrieli, 2002; Luna & Sweeney, 2004) relative to children, again suggesting that mature cognitive control involves the ability to efficiently adapt to the relevant demands of the task in recruiting attention systems of the posterior parietal regions.

Subsequent fMRI studies by our group and others (Vaidya et al., 1998; Durston et al., 2002; Booth et al., 2003; Durston et al., 2003) have shown the importance of subcortical systems such as the striatum in overriding inappropriate responses. Striatal regions interact with the prefrontal cortex through direct connections and indirectly through thalamocortical circuits (Alexander, De Long, & Strick, 1986; Alexander & Crutcher, 1990; Alexander, Crutcher, & DeLong, 1990). The importance of the striatum, specifically the caudate nucleus, in cognitive control is highlighted by the finding that children and adolescents with attention deficit hyperactivity disorder (ADHD) have less activity in this region. The lack of activity in this region during go/nogo tasks is paralleled by poorer performance (Rubia et al., 1999; Durston et al., 2003), and both activity in this region and performance differences are normalized with stimulant medications (Vaidya et al., 1998).

Overall, these findings suggest an important role of cortical and subcortical regions, and fine tuning of connections among these regions, in the development of cognitive control. However, control of our thoughts and actions are clearly influenced by the specific context in which they occur. For this reason, both cognitive and social contextual information must be considered when examining the neural processes underlying cognitive control.

Development of affective control. Emotional context can differentially impact the recruitment of cognitive control. For example, positive emotional valence is related to approach and reward, whereas negative valence is associated with avoidance and withdrawal (Davidson, Ekman, Saron, Senulis, & Friesen, 1990; O'Doherty et al., 2003). Throughout this paper we have shown that immature cognition is characterized by susceptibility to interfering information. In a separate series of experiments, we examined cognitive control in the context of approaching and avoiding emotional information (positive and negative). We collected behavioral data from 100 subjects ranging in age from 5 to 34 years using a go/nogo task that included emotional facial expressions as stimuli (Casey & Tottenham, submitted). The task required subjects to approach (go trials) or avoid (nogo trials) specific facial expressions (happy, sad, fearful and angry) in the context of neutral faces. Based on the idea that happy expressions are positive and associated with approach related goals, whereas negative expressions like fearful, angry, and sad are more associated with avoidance and withdrawal (Davidson et al., 1990), we predicted that performance on a go/nogo task would be biased by the emotional valence of the go and nogo stimuli. We found that across all ages, subject reaction times were faster when approaching positive expressions (happy) relative to negative expressions (fearful, angry, and sad) and that accuracy was

higher when approaching emotional expressions relative to neutral expressions. This difference was primarily driven by the fact that accuracy was higher when approaching, as opposed to avoiding, happy expressions, as subjects had more difficultly avoiding happy expressions.

Developmental differences in the effects of emotional information on cognitive control were seen in terms of both reaction times and accuracy. While overall accuracy improved linearly with age, reaction times showed a U-shaped pattern with older children and adolescents, being faster than adults, to go trials, especially positive go trials. There was an interaction of gender with age and emotion. Relative to adults, girls 8 and younger were slower to approach emotional stimuli, particularly fearful faces, in contrast to boys of the same age who had faster reaction times, especially for positive expressions. These results suggest a stronger bias toward positive information in males during early development, which parallels greater impulsivity during this period of development for boys. Longer response times to fearful expressions by young girls relative to boys may reflect enhanced processing of emotional expressions in females previously reported by our lab (Thomas et al., 2001) and others (see McClure, 2000).

Neural Substrates of Affective and Cognitive Control. Interactions between cognitive and emotional processes play an important role in behavior regulation and its development as described above. While the neural basis of these interactions is not yet completely understood, we do know that reciprocal connections exist between prefrontal control regions and subcortical regions involved in emotion processing, in particular the amygdala and nucleus accumbens (e.g. Haber, Groenewegen, Grove, & Nauta, 1985; Amaral, 1986; McDonald, 1987; Groenewegen, Berendse, & Haber, 1993; Haber, Kunishio, Mizobuchi, & Lynd-Balta, 1995; Ghashghaei & Barbas, 2002) Animal studies have shown the importance of prefrontal connections with the amygdala and nucleus accumbens in aversive (avoidance) and appetitive (approach) conditioning, respectively (LeDoux, 1995; Garcia, Vouimba, Baudry, & Thompson, 1999; Parkinson, Cardinal, & Everitt, 2000a; Parkinson, Willoughby, Robbins, & Everitt, 2000b; Cardinal, Parkinson, Hall, & Everitt, 2002; Parkinson et al., 2002). Neuroimaging studies of affective control in adults suggest a role for top down prefrontal modulation of subcortical regions associated with emotion processing (Hariri, Bookheimer, & Mazziotta, 2000; Ochsner, Bunge, Gross, & Gabrieli, 2002; Hariri, Mattay, Tessitore, Fera, & Weinberger, 2003; Keightley et al., 2003; Lange et al., 2003; Nomura et al., 2004; Ochsner et al., 2004).

We have begun to examine the neural substrates underlying the cognitive and affective processes in our emotional go/nogo task using fMRI in adults (Hare et al., in press). Task performance in the scanner is consistent with our behavioral study, subjects are slower to respond to fearful expressions and make more false alarms when inhibiting responses to happy expressions. The neuroimaging data show that emotional information influences patterns of neural activity as well as behavioral performance. In our study, greater activation was seen in the ventral

amygdala, a region repeatedly implicated in fear conditioning and evaluating the emotional significance of a stimulus (e.g. LeDoux, 1998; Whalen et al., 1998) when subjects approached negative targets. Activation in this region correlated with reaction time with greater activity in this region for slower responses. Thus negative valence and amygdala activation was related to impaired task performance.

In contrast, positive emotional stimuli were found to influence behavior and neural activity differently (Hare et al., in press). Compared to fearful expressions, happy expressions elicited greater activity in the nucleus accumbens, a region associated with reward and appetitive behavior (see Schultz, Tremblay, & Hollerman, 2000; Nestler, 2004). Therefore, activation of the amygdala is associated with avoidance of negative emotional valence, while activation of the nucleus accumbens is related to approaching positive emotional valence. This bias towards approaching positive emotional information could explain why subjects made more false alarms to happy relative to negative expressions.

As shown previously, frontostriatal control circuits are involved in overcoming interference from competing sources. Enhanced recruitment of these frontostriatal regions implicated in non-emotional go-nogo tasks was seen during the current task when subjects successfully inhibited responses to positive expressions over neutral or negative ones. These regions, specifically the right caudate nucleus, correlated with performance such that subjects with more caudate activity made fewer false alarms to happy expressions. These findings suggest that increased activation of frontostriatal regions involved in cognitive control is associated with effectively overriding the influence of interfering emotional information.

Developmental studies of affective control reveal distinct patterns of brain activity that are similar to patterns of activity seen in the development of cognitive control (Monk et al., 2003; Levesque et al., 2004). In a study using a selective attention task superimposed on emotional information (Monk et al., 2003), adolescents showed greater activity in the amygdala, while adults had greater activity in ventral prefrontal cortex. Further, adults modulated prefrontal activity in response to task demands (attend to fearful face vs non-emotional feature), while in adolescents, activity did not differ between conditions. This finding is consistent with immature cognition being characterized by increased susceptibility to irrelevant information. Similarly, children appear to recruit a greater number of prefrontal regions when attempting to suppress emotional responses (Levesque et al., 2004) compared to adults performing the same task (Levesque et al., 2003). Again, suggesting a transition from diffuse to more focal (fine-tuned) patterns of prefrontal activity with development. One caveat to the findings of Levesque and colleagues is that children and adults were examined in two separate experiments and not directly compared to one another. Thus, until confirmed by a direct comparison between age groups, these results must be interpreted with caution.

Conclusion

The efficiency of cognitive control continues to improve throughout childhood and adolescence. Immature cognitive control is characterized by susceptibility to interference, but with maturity the ability to recruit additional resources to override competition is enhanced. Investigations of cognitive control in emotional contexts show that emotional valence continues to influence performance and neural activity in childhood and adulthood. In functional imaging studies, behavioral performance on tasks that require cognitive control correlates with activity in frontostriatal regions, especially in overcoming interference due to preceding or emotional contexts in order to make the appropriate response.
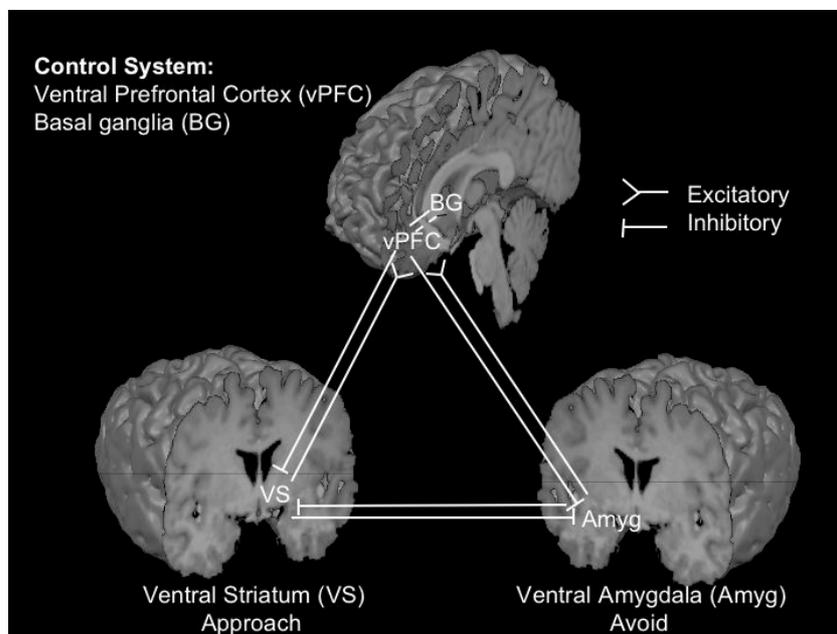

Figure 1. Interactions between prefrontal, amygdala, and striatal circuits in suppressing actions and emotions. Effective prefrontal regulation of subcortical regions is a key aspect of mature cognition.

We propose a neurobiological model of cognitive and affective control in which the prefrontal cortex modulates subcortical systems in order to support goal-oriented behavior (see Figure 1 above). Amygdalo-prefrontal connections promote the avoidance of negative and potentially dangerous stimuli. Conversely, signals to the prefrontal cortex from the ventral striatum, which includes the nucleus accumbens, enhance the tendency to approach positive and reward related stimuli.

Information about the emotional valence of a stimulus is often beneficial to decision-making. However, when emotional information is irrelevant or contrary to the current goal, top-down connections from the prefrontal cortex to subcortical regions, the final link in our model, are critical for regulating the effects of affective information on cognitive processes.

The model proposed above, while clearly an overly simplified model, provides a theoretical framework for designing experiments aimed at determining the neurobiological substrates of interactions between cognitive and emotional processes. Collectively, the available data indicate that prefrontal networks are a critical aspect of these interactions. We suggest that developmental changes in neural circuits involving the prefrontal cortex contribute to the emergence of adult cognitive and emotional regulation. Therefore, development could be a useful tool in delineating the contributions of different brain regions (e.g., prefrontal cortex) to cognitive and affective control. Given the protracted maturation of prefrontal cortex relative to subcortical regions (see Sowell et al., 2003; Giedd, 2004) one would expect to see a shift from greater activity in subcortical regions like the amygdala and nucleus accumbens in childhood to increased prefrontally-mediated processing in adults. Future studies that explore the mechanisms of maturational changes in prefrontal networks will further our understanding of how we learn to regulate behavior in both cognitive and social contexts.

REFERENCES

Alexander, G. E., & Crutcher, M. D. (1990). Functional architecture of basal ganglia circuits: neural substrates of parallel processing. *Trends in Neuroscience 13,* 266-71.

Alexander, G. E., Crutcher, M. D., & DeLong, M. R. (1990). Basal ganglia-thalamocortical circuits: parallel substrates for motor, oculomotor, "prefrontal" and "limbic" functions. *Progress in Brain Research 85,* 119-46.

Alexander, G. E., DeLong, M. R., & Strick, P. L. (1986). Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annual Review of Neuroscience 9,* 357-381.

Allport, A. (1987). Selection for action: some behavioral and neurophysiological considerations of attention and action. H. H. A. F. Sanders (Ed.), *Perspectives on Perception and Action*. Hillsdale, NJ: Laurence Erlbum Associates.

Amaral, D. G. (1986). Amygdalohippocampal and amygdalocortical projections in the primate brain. *Advvancess in Experimental Medicine and Biology 203,* 3-17.

Baddeley, A. D. (1986). *Working Memory*. New York: Oxford University Press.

Booth, J. R., Burman, D. D., Meyer, J. R., Lei, Z., Trommer, B. L., Davenport, N. D., Li, W., Parrish, T. B., Gitelman, D. R., & Mesulam, M. M. (2003). Neural development of selective attention and response inhibition. *Neuroimage 20*, 737-51.

Brainerd, C. J., & Reyna, V. F. (1993). Memory independence and memory interference in cognitive development. *Psychological Review, 100,* 42-67.

Braver, T. S., & Cohen, J. D. (2000). On the control of control: The role of dopamine regulting prefrontal function and working memory. In S. Monsell & J.Driver (Eds.),

Control of Cognitive Processes. Attention and Performance XVIII. Cambridge, MA, MIT Press. XVIII.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J,& Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron, 33,* 301-11.

Campos, J. J., Mumme, D. L., Kermoian, R., & Campos, R. G. (1994). A functionalist perspective on the nature of emotion. *Monographs of the Society in Research in Child Development, 59*, 284-303.

Cardinal, R. N., Parkinson, J. A., Hall, J., & Everitt, B. J. (2002). Emotion and motivation: the role of the amygdala, ventral striatum, and prefrontal cortex. *Neuroscience and Biobehavioral Reviews, 26,* 321-52.

Casey, B. J., Galvan, A, & Hare, T. A. (in press). Changes in Cerebral Functional Organization with Cognitive Development. *Current Opinion in Neurobiology.*

Casey, B. J., & Tottenham, N. (submitted). Development of affect regulation: A normative study.

Casey, B. J., Tottenham, N.,& Fossella, J. (2002). Clinical, imaging, lesion, and genetic approaches toward a model of cognitive control. *Developmental Psychobiology, 40,* 237-54.

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., Castellanos, F. X., Haxby, J. V., Noll, D. C., Cohen, J. D., Forman, S. D., Dahl, R. E.,& Rapoport, J. L. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of Cognitive Neuroscience, 9,* 835-847.

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: a connectionist approach to behavior and biology in schizophrenia. *Psychology Review, 99*, 45-77.

Cole, P. M., Martin, S. E., & Dennis, T. A. (2004). Emotion regulation as a scientific construct: methodological challenges and directions for child development research. *Child Development, 75,* 317-33.

Cole, P. M., Michel, M. K., & Teti, L. O. (1994). The development of emotion regulation and dysregulation: a clinical perspective. *Monographs of the Society for Research in Child Development, 59,* 73-100.

Davidson, R. J., Ekman, P., Saron, C. D., Senulis, J. A., & Friesen, W. V. (1990). Approach-withdrawal and cerebral asymmetry: emotional expression and brain physiology. *Journal of Personality and Social Psychology, 58*, 330-41.

Dempster, F. N., Ed. (1993). Resistance to interference: Developmental changes in a basic processing mechanism. *Emerging Themes in Cognitive Development: Volume 1: Foundations.* New York, Springer-Verlag.

Derryberry, D., & Rothbart, M. K. (1988). Arousal, affect, and attention as components of temperament. *Journal of Personality and Social Psychology, 55,* 958-66.

Derryberry, D., & Rothbart, M. K. (1997). Reactive and effortful processes in the organization of temperament. *Development and Psychopathology, 9,* 633-652.

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

Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development, 56*, 868-883.

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

Durston, S., Tottenham, N. T., Thomas, K. M., Davidson, M. C., Eigsti, I. M., Yang, Y., Ulug, A. M., & Casey, B. J. (2003). Differential patterns of striatal activation in young children with and without ADHD. *Biological Psychiatry, 53,* 871-8.

Fox, N. A. (1994). Dynamic cerebral processes underlying emotion regulation. *Monographs of the Society for Research in Child Development, 59,* 152-66.

Frijda, N. H. (1988). The laws of emotion. *American Journal of Psychology, 43,* 349-58.

Garcia, R., Vouimba, R. M., Baudry, M., & Thompson, R. F. (1999). The amygdala modulates prefrontal cortex activity relative to conditioned fear. *Nature, 402*, 294-6.

Ghashghaei, H. T., & Barbas, H. (2002). Pathways for emotion: interactions of prefrontal and anterior temporal pathways in the amygdala of the rhesus monkey. *Neuroscience, 115*, 1261-1279.

Giedd, J. N. (2004). Structural magnetic resonance imaging of the adolescent brain. *Annls of the New York Academy Sciences, 1021,* 77-85.

Groenewegen, H. J., Berendse, H. W., & Haber, S. N. (1993). Organization of the output of the ventral striatopallidal system in the rat: ventral pallidal efferents. *Neuroscience 57,* 113-42.

Haber, S. N., Groenewegen, H. J., Grove, E. A., & Nauta, W. J. (1985). Efferent connections of the ventral pallidum: evidence of a dual striato pallidofugal pathway. *The Journal of Comparative Neurology, 235,* 322-35.

Haber, S. N., Kunishio, K., Mizobuchi, M., & Lynd-Balta, E. (1995). The orbital and medial prefrontal circuit through the primate basal ganglia.*The Journal of Neuroscience, 15,* 4851-67.

Hare, T., Tottenham, N., Davidson, M. C., Glover, G. H., & Casey, B. J. (submitted). Contributions of striatal and amygdala activity in emotion regulation.

Hariri, A. R., Bookheimer, S. Y., & Mazziotta, J. C. (2000). Modulating emotional responses: effects of a neocortical network on the limbic system. *Neuroreport, 11*, 43-8.

Hariri, A. R., Mattay, V. S., Tessitore, A., Fera, F., & Weinberger, D. R. (2003). Neocortical modulation of the amygdala response to fearful stimuli. *Biological Psychiatry, 53*, 494-501.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice Hall.

Keightley, M. L., Winocur, G., Graham, S. J., Mayberg, H. S., Hevenor, S. J., & Grady, C. L. (2003). An fMRI study investigating cognitive modulation of brain regions associated with emotional processing of visual stimuli. *Neuropsychologia, 41,* 585-96.

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, I. E., Weisskoff, R. M., Poncelet, B. P., Kennedy, D. N., Hoppel, B. E., Cohen, M. S., Turner, R., Cheng, H., Brady, T. J., & Rosen, B. R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceeding of the National Academy of Sciences USA, 89*, 5675-9.

Lange, K., Williams, L. M., Young, A. W., Bullmore, E. T., Brammer, M. J., Williams, S. C., Gray, J. A., & Phillips, M. L. (2003). Task instructions modulate neural responses to fearful facial expressions. *Biological Psychiatry, 53,* 226-32.

LeDoux, J. (1998). Fear and the brain: where have we been, and where are we going? *Biological Psychiatry, 44,* 1229-38.

LeDoux, J. E. (1995). Emotion: Clues from the brain. *Annual Review of Psychology, 46,* 209-35.

Levesque, J., Eugene, F., Joanette, Y., Paquette, V., Mensour, B., Beaudoin, G., Leroux, J. M., Bourgouin, P., & Beauregard, M. (2003). Neural circuitry underlying voluntary suppression of sadness. *Biological Psychiatry, 53,* 502-10.

Levesque, J., Joanette, Y., Mensour, B., Beaudoin, G., Leroux, J. M., Bourgouin, P., & Beauregard, M. (2004). Neural basis of emotional self-regulation in childhood. *Neuroscience, 129,* 361-9.

Luna, B., & Sweeney, J. A. (2004). The emergence of collaborative brain function: FMRI studies of the development of response inhibition. *Annals of the New York Academy of Sciences, 1021,* 296-309.

Luna, B., Thulborn, K. R., Munoz, D. P., Merriam, E. P., Garver, K. E., Minshew, N. J., Keshavan, M. S., Genovese, C. R., Eddy, W. F., & Sweeney, J. A. (2001). Maturation of widely distributed brain function subserves cognitive development. *NeuroImage, 13,* 786-93.

Luria, D. M. (1961). *The role of speech in the regulation of normal and abnormal behavior.* New York: Liveright.

McClure, E. B. (2000). A meta-analytic review of sex differences in facial expression processing and their development in infants, children, and adolescents. *Psychological Bulletin, 126,* 424-53.

McDonald, A. J. (1987). Organization of amygdaloid projections to the mediodorsal thalamus and prefrontal cortex: a fluorescence retrograde transport study in the rat. *The Journal of Comparative Neurology, 262,* 46-58.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Mischel, W. (1958). Preference for delayed reinforcement: an experimental study of a cultural observation. *Journal of Abnormal Child Psychology, 56,* 57-61.

Mischel, W. (1961). Preference for delayed reinforcement and social responsibility. *Journal of Abnormal and Social Psychology , 62,* 1-7.

Mischel, W. (1966). Theory and research on the antecedents of self-imposed delay of reward. *Progress in Experimental Personality Research, 3,* 85-132.

Mischel, W., & Metzner, R. (1962). Preference for delayed reward as a function of age, intelligence, and length of delay interval. *Journal of Abnormal and Social Psychology, 64,* 425-31.

Mischel, W., & Underwood, B. (1974). Instrumental ideation in delay of gratification. *Child Development, 45,* 1083-8.

Monk, C. S., McClure, E. B., Nelson, E. E., Zarahn, E., Bilder, R. M., Leibenluft, E., Charney, D. S., Ernst, M., & Pine, D. S. (2003). Adolescent immaturity in attention-related brain engagement to emotional facial expressions. *NeuroImage,* 20, 420-8.

Morton, J. B., & Munakata, Y. (2002). Active versus latent representations: a neural network model of perseveration, dissociation, and decalage. *Developmental Psychobiology, 40,* 255-65.

Munakata, Y., & Yerys, B. E. (2001). All together now: when dissociaations between knowledge and action disappear. *Psychological Science, 12*, 335-337.

Nestler, E. J. (2004). Molecular mechanisms of drug addiction. *Neuropharmacology 47 Suppl 1,* 24-32.

Nomura, M., Ohira, H., Haneda, K., Iidaka, T., Sadato, N., Okada, T., & Yonekura, Y. (2004). Functional association of the amygdala and ventral prefrontal cortex during cognitive evaluation of facial expressions primed by masked angry faces: an event-related fMRI study. *NeuroImage, 21,* 352-63.

O'Doherty, J., Winston, J., Critchley, H., Perrett, D., Burt, D. M., & Dolan, R. J. (2003). Beauty in a smile: the role of medial orbitofrontal cortex in facial attractiveness. *Neuropsychologia, 41,* 147-55.

Ochsner, K. N., Bunge, S. A., Gross, J. J., & Gabrieli, J. D. (2002). Rethinking feelings: an FMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience, 14*, 1215-29.

Ochsner, K. N., Ray, R. D., Cooper, J. C., Robertson, E. R., Chopra, S., Gabrieli, J. D., & Gross, J. J. (2004). For better or for worse: neural systems supporting the cognitive down- and up-regulation of negative emotion. *NeuroImage, 23,* 483-99.

Ogawa, S., Tank, D. W., Menon, R., Ellermann, J. M., Kim, S. G., Merkle, H.,& Ugurbil, K. (1992). Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. *Proceedings of the National Academy of Sciences USA, 89,* 5951-5.

Parkinson, J. A., Cardinal, R. N., & Everitt, B. J. (2000). Limbic cortical-ventral striatal systems underlying appetitive conditioning. *Progress in Brain Research, 126*, 263-85.

Parkinson, J. A., Dalley, J. W., Cardinal, R. N., Bamford, A., Fehnert, B., Lachenal, G., Rudarakanchana, N., Halkerston, K. M., Robbins, T. W., & Everitt, B. J. (2002). Nucleus accumbens dopamine depletion impairs both acquisition and performance of appetitive Pavlovian approach behaviour: implications for mesoaccumbens dopamine function. *Behavioural Brain Research, 137,* 149-63.

Parkinson, J. A., Willoughby, P. J., Robbins, T. W., & Everitt, B. J. (2000). Disconnection of the anterior cingulate cortex and nucleus accumbens core impairs Pavlovian approach behavior: further evidence for limbic cortical-ventral striatopallidal systems. *Behavioural Neuroscience, 114*, 42-63.

Piaget, J. (1954). *The construction of reality in the child.* New York: Basic Books.

Posner, M. ,& Boies, S. J. (1971). Components of Attention. *Psychological Review, 78*, 391-408.

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

Posner, M. I., & Snyder, C. R. (1975). *Attention and cognitive control.* Hillsdale, NJ: Erlbaum.

Rothbart, M. K., & Ahadi, S. A. (1994). Temperament and the development of personality. *Journal of Abnormal Psychology, 103*, 55-66.

Rothbart, M. K., Derryberry, D., & Posner, M. (1994). A psychobiological approach to the development of temperament. In J. E. Bates & T. D. Wachs (Eds.), *Temperament: Individual differences in biology and behavior.* Washington D.C.: American Psychological Association.

Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S. C., Simmons, A. ,& Bullmore, E. T. (1999). Hypofrontality in attention deficit hyperactivity disorder during higher-order motor control: a study with functional MRI. *American Journal of Psychiatry, 156*, 891-6.

Schultz, W., Tremblay, L., & Hollerman, J. R. (2000). Reward processing in primate orbitofrontal cortex and basal ganglia. *Cerebral Cortex, 10*, 272-84.

Shallice, T. (1988). *From neuropsychology to mental structure.* New York: Cambridge University Press.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84*, 127-190.

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., & Toga, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience, 6,* 309-15.

Thomas, K. M., Drevets, W. C., Whalen, P. J., Eccard, C. H., Dahl, R. E., Ryan, N. D., & Casey, B. J. (2001). Amygdala response to facial expressions in children and adults. *Biological Psychiatry, 49*, 309-16.

Tipper, S. P., Bourque, T. A., Anderson, S. H., & Brehaut, J. C. (1989). Mechanisms of attention: A developmental study. *Journal of Expperimental Child Psychology, 48,* 353-378.

Toner, I. J., & Smith, R. A. (1977). Age and Overt verbalization in delay-maintenance behavior in children. *Journal of Experimental Child Psychology, 24*, 123-128.

Turner, R., Le Bihan, D., Moonen, C. T., Despres, D., & Frank, J. (1991). Echo-planar time course MRI of cat brain oxygenation changes. *Magnetic Resonance in Medicine, 22,* 159-66.

Vaidya, C. J., Austin, G., Kirkorian, G., Ridlehuber, H. W., Desmond, J. E., Glover, G. H.,& Gabrieli, J. D. (1998). Selective effects of methylphenidate in attention deficit hyperactivity disorder: a functional magnetic resonance study. *Proceedings of the National Academy of Sciences USA, 95*, 14494-9.

Walls, R. T.,& Smith, T. S. (1970). Development of preference for delayed reinforcement in disadvantaged children. *Journal of Educational Psychology, 61,* 118-23.

Whalen, P. J., Rauch, S. L., Etcoff, N. L., McInerney, S. C., Lee, M. B., & Jenike, M. A. (1998). Masked presentations of emotional facial expressions modulate amygdala activity without explicit knowledge. *Journal of Neuroscience, 18,* 411-8.

Zelazo, P. D., Burack, J. A., Benedetto, E., & Frye, D. (1996). Theory of mind and rule use in individuals with Down's syndrome: a test of the uniqueness and specificity claims. The *Journal of Child Psychology and Psychiatry, 37*, 479-84.