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8 Emotion Regulation from the Perspective of Developmental Neuroscience

What, Where, When, and Why

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INTRODUCTION

Imagine that a loved one has been diagnosed with a serious illness. What is your response to this devastating news and how will you cope? The emotion regulation researcher can ask this question from numerous perspectives: How intense is your emotional reaction? Do you suppress your emotions or "think on the bright side" and hope for the best? How will your emotional reactions differ if you're depressed rather than anxious? Such questions are only the tip of the iceberg in terms of the possibilities an emotion regulation researcher might choose to pursue.

Some of the most exciting research on emotion regulation to emerge recently uses the highly sensitive tools of neuroscience to pursue and refine some of these challenging questions. Yet, research on the neuroscience of child emotion regulation has been relatively slow to develop. Moreover, in research with children, there is a trend to apply emotion regulation theories developed in reference to adults without carefully considering developmental principles. This could limit the ability of researchers to detect emotion regulatory processes that might be critical factors in childhood, but less important in adulthood.

The first goal of this chapter is a descriptive one: To critically highlight trends in neuroscience research examining emotion regulation. We argue that a neural biomarker approach has the potential to strengthen and clarify how the field conceptualizes and measures the construct of emotion regulation, and articulates how emotion regulation relates to the development of both positive adjustment and psychopathology. The second goal of this chapter is more prescriptive: To advance developmental neuroscience research on emotion regulation, we must integrate findings from diverse fields, highlight developmental principles, and ground empirical questions in both behavioral and neuroscience principles. Moreover, given the complexity of the construct of emotion regulation, there is a need to improve communication and comparisons across labs, as well as to clarify what we mean by the construct of emotion regulation. To this end, we propose the "FourW Framework," which describes four key domains of inquiry in the field of emotion regulation research: *What* is being regulated?, *Where* is regulation occurring?, *When* is regulation occurring?, and *Why* is regulation occurring? (e.g., see also Dennis, Buss, & Hastings, 2012). Based on this and our review of the literature, we make recommendations for future developmental neuroscience research on emotion regulation.

Our discussion opens by outlining some of the central definitions and models of emotion regulation that inform neuroscience research, followed by a selective review of the neuroscience literature relevant to understanding the development of emotion regulation.

DEFINITIONS AND MODELS OF EMOTION REGULATION

The concept of emotion regulation enjoys substantial attention in research with adults (Gross, 1998b), children (Cole, Martin, & Dennis, 2004), and from a neuroscience perspective (Ochsner, Bunge, Gross, & Gabrieli, 2002). The increasing number of popular (e.g. Chapman, 2010; Meyer, 2002) and scientific books (e.g., Fox, 1994; Gross, 2007; Kring & Sloan, 2010; Philippot & Feldman, 2004) also attests to the popularity of emotion regulation. Yet, due to definitional vagueness and disagreements, some have commented that we have reached an impasse in terms of the scientific utility of the construct; that is, it is not clear how emotion regulation is distinct, and what it "buys" us above and beyond similar concepts like self-regulation (Baumeister, Zell, & Tice, 2007), emotional intelligence (Joseph & Newman, 2010), emotion (Campos, Frankel, & Camras, 2004), and temperament (Derryberry & Rothbart, 1997; Volling, 2001).

However, amid some debate, there appears to be increasing convergence among definitions of emotion regulation (Bloch, Moran, & Kring, 2010). In the most general sense, regulation in biological and medical contexts refers to "the adaption of form or behavior of an organism to changed conditions" (http://www.biology-online.org). From the Latin root *regula* (rule), regulation also involves the monitoring of a particular situation or reaction. Thus, regulation concerns adaptation to an internal or external event as well as the ongoing monitoring of that adaptation. Current influential definitions of emotion regulation reflect this focus on internal and external context, monitoring, and change. We will highlight only a few here, most relevant to the developmental neuroscience literature (for other definitions, see also Campos et al., 2004; Dodge, 1989; Gratz & Roemer, 2004).

Thompson (1994) defines emotion regulation as consisting of "the extrinsic and intrinsic processes responsible for monitoring, evaluating, and modifying emotional reactions, especially in their intensive and temporal features, to accomplish one's goals." Another influential definition is from Gross (1998b): "The processes by which individuals influence which emotions they have, when they have them, and how the experience and express their emotions." In addition to this definition, Gross further deconstructs emotion regulation into a five-stage emotion-generative process, where emotion regulation can occur at any point: situation selection, situation modification, attentional deployment, cognitive change, and response modulation. More recently, Gross and Thompson (2007) collaborated on a conceptualization of emotion regulation that represents an integration of their respective focuses on intrinsic and extrinsic processes in emotion regulation: "Emotion regulation refers to the automatic or controlled, conscious or unconscious process of individual influencing emotion in self, others, or both."

The five-stage model of emotion regulation (Gross, 1998b; Gross & Thompson, 2007) has been particularly influential in neuroscience studies of emotion regulation. For example, functional magnetic resonance imaging (fMRI; e.g., Phan et al., 2005), scalp recorded event-related potentials (ERPs) (e.g., Foti & Hajcak, 2008), and physiological (e.g., Gross & Levenson, 1997, 1993) studies have examined biological underpinnings of two strategies: cognitive reappraisal (altering the emotional significance of an emotional situation, such as by reinterpreting an unpleasant situation in a more positive light) and expressive suppression (suppressing the expression of emotion), the former occurring at the stage of cognitive change and the latter occurring at the level of response modulation. In general, although expressive suppression serves to alter the expression of emotion, it may be less effective in modulating emotional experiences; moreover, expressive suppression compared to cognitive reappraisal carries with it physiological costs that could compromise health (Gross, 1998a; Gross & Levenson, 1993; Gross & Levenson, 1997).

Cole et al. (2004) highlight the importance of these definitions of emotion regulation, which emphasize instances in which emotions are shaped, directed, and controlled by top-down control and inhibitory processes (Dennis, 2010). However, they also argue that these models do not carefully consider how emotions themselves are regulating of other emotions (e.g., using anger to regulate sadness), cognition (e.g., emotions constraining attention), and behavior (e.g., emotions influencing behavioral choices (Dennis, Cole, Wiggins, Cohen, & Zalewski, 2009; Gray, 2004; Luu & Tucker, 2004). Thus, from this perspective, a complete consideration of emotion regulation must encompass instances in which emotions are regulat*ed* and regulat*ing*.

Some have suggested that this approach to emotion regulation is too broad (Eisenberg & Spinrad, 2004) and makes emotion regulation too similar to the construct of emotion (Gross & Thompson, 2007), which may be fundamentally regulatory (Campos et al., 2004; Frijda, 1986). However, if we acknowledge key tenets of functional emotion theory—that emotions are fundamentally action readiness tendencies that direct and motivate behavior, and that the expression and experience of emotions are non-linear, dynamic, and reciprocally interconnected with other processes (Campos et al., 2004; Frijda, 1986; Izard & Ackerman, 2000)—then emotions should also regulate the control processes that in turn are thought to regulate emotions. Because of this possibility, to not consider ways in which emotions are regulating may miss something fundamental about the nature of emotion regulation. At the same time, this complexity requires that we carefully define what aspect of emotion regulation we are examining.

However one views these definitional issues, the emotion regulation researcher is faced with a challenge that reductionism cannot overlook—we need more sophisticated ways to infer when and how emotion regulation occurs. In this chapter, we highlight the role that neuroscience and developmental neuroscience in particular can play in teasing apart many of these questions.

NEURAL UNDERPINNING OF EMOTION REGULATION

The development of emotion regulation is shaped by emotional reactivity, control and inhibitory processes, and the interplay between the two (Derryberry & Rothbart, 1997; Henderson & Wachs, 2007; Luu & Tucker, 2004). Similarly, the neuroscience literature on emotion regulation has described the "neural architecture" of emotion regulation in a way that distinguishes between two complementary but highly interconnected neural systems: a ventral system that underlies emotional arousal, emotional significance evaluation, and motivational processes and a dorsal system that underlies relatively effortful, executive control functions such as attention regulation and cognitive control (Critchley, 2005; Dolan, 2002; Luu, Tucker, & Derryberry, 1998).

The ventral system is sensitive to information that is motivationally significant, and thus capitalizes on rapid and relatively automatic evaluative and regulatory processes. This system is activated under emotional conditions and is modulated by the use of cognitive emotion regulation strategies such as reappraisal. In emotion regulation research, four key structures have been emphasized: the amygdala, the insula, the striatum, and the medial orbitofrontal cortex (MOFC).

The amygdala is comprised of multiple nuclei which have been functionally linked to both learning and expressing the fear response (LeDoux, 2000). The amygdala is also sensitive to the presence of threat-relevant stimuli like angry faces and pictures of threatening situations (Whalen et al., 1998), although in children the amygdala may be sensitive to a broader range of stimulus types (Thomas et al., 2001). The insula has been examined in emotion regulation research due to its wide variety of functions, including visceral sensory, somatosensory, motor, and language (Augustine, 1996). It is additionally conceptualized as a limbic integration area and it receives afferent input from the viscera and thus is implicated in aversive affective experiences (Damasio et al., 2000; Lévesque, Eugène, Joanette, Paquette, Mensour, Beaudoin, et al., 2003). Reappraisal studies have shown that both amygdala and insula activity is reduced when participants are asked to reduce negative emotion via cognitive reappraisal, suggesting decreased emotional reactions due to the use of an emotion regulation strategy (e.g., Ochsner et al., 2002; Phan et al., 2005; Urry et al., 2006).

The striatum and MOFC show less clear associations with emotion regulation. The striatum is part of the basal ganglia and includes the caudate and putamen. The striatum is linked to processing and anticipation of rewards (e.g., Delgado, Locke, Stenger, & Fiez, 2003; Knutson, Fong, Adams, Varner, & Hommer, 2001) but has also been associated with the induction of happiness (Phan, Wager, Taylor, & Liberzon, 2002) and the detection of unexpected, salient stimuli (Zink, Pagnoni, Martin, Dhamala, & Berns, 2003). Some studies show that activity in the striatum is reduced during emotion regulation (e.g., Phan et al., 2005), and others show increased activity in the dorsal striatum (e.g., van Reekum, Johnstone, Urry, Thurow, Schaefer, Alexander, et al., 2007). This could reflect, among other things, the role of the striatum in learning or improving emotion regulation strategies. The MOFC is active under conditions that require encoding of affective value in relation to one's goals. Like the striatum, links with emotion regulation are unclear: The MOFC is more active when participants are asked to attend to rather than reappraise an unpleasant stimulus (Ochsner et al., 2002), but this association is not consistent across studies (Ochsner et al., 2004).

This dorsal network, in contrast, supports the ability to regulate arousal in more deliberate ways and utilizes motivationally relevant information from the ventral network to direct attention and memory and to plan actions. This system is activated during reappraisal and reflects executive control processes that serve to modulate emotional experiences and processing (e.g., Johnstone, van Reekum, Kalin, & Davidson, 2007; Ochsner et al., 2002; Ochsner et al., 2004; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008). Four key areas of the prefrontal cortex have been implicated in the use of cognitive emotion regulation strategies: the lateral prefrontal cortex (LPFC), the medial PFC (MPFC), the lateral orbitofrontal cortex (LOFC), and the anterior cingulate cortex (ACC). Because the prefrontal cortex supports executive functions such as cognitive monitoring, planning, and working memory, these prefrontal structures are thought to be central to the ability to generate and maintain regulatory strategies and to integrate cognitive interpretations of stimuli with more bottom-up affective processes, such as motives, emotional reactivity, and visceral experiences.

The LPFC, particularly the dorsolateral (DLPFC) and ventrolateral PFC (VLPFC), are consistently activated in studies examining the up- and down-regulation of negative affect via reappraisal (e.g., Goldin, McRae, Ramel, & Gross, 2008; Ochsner et al., 2002; Ochsner et al., 2004; Opitz, Rauch, Terry, & Urry, 2012). These areas of the LPFC are thought to be important for maintaining and manipulating information in working memory and selecting among competing task-relevant information (Callicott et al., 1999), both of which are highly relevant to the ability to select and engage a range of cognitive emotion regulation strategies. The MPFC is also consistently activated in reappraisal studies, but appears to be more sensitive to self-reflection. That is, while active under a range of emotion regulation conditions (Goldin et al., 2008; Ochsner et al., 2002; Phan et al., 2005; Urry et al., 2006; van Reekum et al., 2007), the MPFC is more sensitive to self-referential and self-focused judgments rather than external or situation-focused judgments (Kelley et al., 2002; Ochsner et al., 2004). In contrast, the LOFC may be more contextually sensitive by guiding reappraisal strategies through the selection of context-appropriate behaviors. Also active during the down-regulation of negative emotion via reappraisal (Goldin et al., 2008; Phan et al., 2005), increases in activity of the LOFC have been positively correlated with reduced subjective sadness (Lévesque et al., 2003).

The ACC serves as an intermediary or relay station between functions of the ventral and dorsal networks, and thus is a key structure in emotion regulation (Bush, Luu, & Posner, 2000; Luu & Tucker, 2004). Anterior portions of the cingulate cortex are extensively interconnected with a host of neural regions, such as lateral prefrontal cortex, parietal cortex, limbic and paralimbic regions, as well as efferent connections with autonomic, visceral, motor, and endocrine systems (Bush et al., 2000; Whalen et al., 1998). Rostral and ventral portions of the ACC are considered to be the affective subdivision of the ACC, and are active under conditions in which emotional information is salient, emotions are induced, and emotion regulation and inhibition are required (Beauregard, Lévesque, & Bourgouin, 2001; Bush et al., 2000; Mayberg, 1997). Functions of the dorsal ACC (dACC) include sensory and response selection, conflict monitoring, error detection, and working memory, leading the dACC to traditionally be characterized as the cognitive subdivision of the ACC (Bush et al., 2000; Carter, MacDonald, Ross, & Stenger, 2001; Dehaene, Posner, & Tucker, 1994; Magno & Allan, 2007).

Recent research suggests that the distinctions and similarities between the affective and cognitive subdivisions of the ACC may be more complex. For example, the dACC is active under both affective and cognitive conditions in which two responses are in competition (Ochsner, Hughes, Robertson, Cooper, & Gabrieli, 2009), is more active during reappraisal, and is negatively correlated with subjective negative emotional arousal (Ochsner et al., 2002; Phan et al., 2005). In addition, the affective and cognitive subdivisions of the ACC are reciprocally active in response to emotional versus cognitive tasks: For example, in a direct comparison, a counting Stroop task activated the cognitive subdivision, while an emotional counting Stroop task activated the affective subdivision (Bush et al., 2000). Taken together, research suggests that the ACC is involved in conflict monitoring that supports the ability to reappraise negative stimuli in a more neutral or positive light. The ACC also appears to be sensitive to the interplay between cognitive and affective demands, and integrates affective information with executive control processes. Given these functions, the ACC is thought to be a key structure underlying adaptive and maladaptive emotion regulation, and is an intermediary between higher order cognition and emotional arousal (Luu & Tucker, 2004; Paus, 2001).

The ventral and dorsal systems are instantiated in strongly interconnected cortico-limbic circuitry, such that dopaminergic structures like the nucleus accumbens and the ventral tegmental area project to the PFC, and in turn all share connections with the amygdala, hippocampus, and hypothalamus. Moreover, the PFC, particularly the medial and dorsal regions, provides important inhibitory inputs into the amygdala (Amaral, Price, Pitkanen, & Carmichael, 1992; Davidson, 2002; Hariri, Bookheimer, & Mazziotta, 2000). Due to these interconnections, regulation can occur either through top-down modulation of emotional reactivity or through bottom-up biasing of cognitive functions through motivational set points and the integration of affective information into cognition (Luu & Tucker, 2004). While most human neuroimaging studies of emotion regulation focuses on cognitive emotion regulation strategies that require working memory, planning, and other high-order cognition operations, more "automatic" forms of emotion regulation should be considered, and may rely on distinct neural regions (Ellenbogen, Schwartzman, Stewart, & Walker, 2006; Ochsner & Gross, 2005). For example, conditioning and extinction learning recruit ventromedial and medial orbital PFC (Quirk & Beer, 2006).

In a recent fMRI study, Kanske and colleagues (Kanske, Heissler, Schonfelder, Bongers, & Wessa, 2011) addressed a rarely examined question—whether distinct types of cognitive emotion regulation strategy differ in their neural mechanisms and effects on emotional experience. They directly compared the use of distraction (arithmetic) and reappraisal to modify responses to emotional pictures. Both strategies reduced subjective emotional arousal and lowered amygdala activity. Distraction, however, resulted in stronger decreases in amygdala activity. Both strategies were associated with increased activity of MPFC, DLPFC, and inferior parietal cortex; the OFC was only active for reappraisal while the dACC and broad areas of the parietal cortex were active for distraction. This study highlights the importance of expanding the range of strategies examined from a neuroscience perspective.

Taken together, neuroimaging studies of emotion regulation thus far emphasize cognitive emotion regulation and report a pattern in which down-regulation of the ventral system and up-regulation of the dorsal system are associated with adaptive emotion regulation. A very small body of neuroscience research has expanded out to examine other forms of regulation, such as social regulation of stress. For example, Coan and colleagues (Coan, Schaefer, & Davidson, 2006) recorded fMRI from married women while they were under the threat of mild electrical shock. During this period, women held their husband's hand, held the hand of an anonymous stranger, or held no hand at all. Physical contact from husbands or strangers reduced neural activity in brain regions associated with both emotional reactivity and cognitive control (e.g., ventral ACC, nucleus accumbens, and DLPFC). Some of these effects were sensitive to spousal relationship quality, with higher quality predicting greater attenuation of the activation. This study suggests that social proximity, in particular with that of a close other, influences basic perception and regulation of threat on the neural level, and that such social regulation may reduce not only the experience of threat but may reduce the need to recruit cognitive resources to initiate other regulatory strategies.

NEUROPHYSIOLOGICAL PROCESSES RELATED TO EMOTION REGULATION: THE LPP

The literature just reviewed uses one neuroimaging technology, fMRI, and focuses on questions concerning the neuroanatomical correlates of emotion regulation. Another growing body of research, however, capitalizes on the superior temporal resolution of electroencephalography (EEG) to examine the time course of affective and cognitive processes underlying the use of emotion regulation strategies. Indeed, some have argued that affective processes, such as emotional attention, must be examined with millisecond precision to fully capture the affective chronometry of emotion-cognition interactions (Banaschewski & Brandeis, 2007; Pessoa, 2010). We will briefly highlight one ERP component here, the late positive potential (LPP), in studies examining cognitive emotion regulation.

The LPP is a positive-going waveform detectable at midline central-parietal electrodes that emerges between 200 and 300 ms following presentation of visual stimuli (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Foti, Hajcak, & Dien, 2009; Schupp, Junghöfer, Weike, & Hamm, 2004). LPP amplitudes are larger to unpleasant and pleasant compared to neutral stimuli (including complex emotional pictures, faces, and words), and thus are thought to reflect increased processing of and facilitated attention to emotional and motivationally significant stimuli (Cuthbert et al., 2000; Moser, Hajcak, Bukay, & Simons, 2006; Schupp et al., 2004). In addition, larger LPP amplitudes are associated with self-reported changes in emotional arousal (Cuthbert et al., 2000; Hajcak & Nieuwenhuis, 2006). Emotional effects on the LPP have been shown to be independent of lower level stimulus characteristics and novelty (Bradley, Hamby, Löw, & Lang, 2007; De Cesarei & Codispoti, 2006) and do not appear to habituate (Breiter et al., 1996; Whalen et al., 1998); other measures such as skin conductance, heart rate, and amygdala activation do habituate (Breiter et al., 1996; Codispoti & De Cesarei, 2007; Codispoti, Ferrari, & Bradley, 2006, 2007). The LPP also appears relatively stable over time and within individuals (Codispoti et al., 2006). For these reasons, and given its excellent temporal resolution, the LPP is particularly appropriate for capturing changes in affective processing and arousal when using emotion regulation strategies.

Several studies have demonstrated the sensitivity of the LPP to emotion regulation instructions to increase and decrease emotion. For example, LPP amplitudes are reduced in response to directions to decrease emotional responses to unpleasant pictures (Moser et al., 2006) and pleasant pictures (Krompinger, Moser, & Simons, 2008). Several other studies showed that the LPP is sensitive to a range of instructions to increase and decrease emotional responses, including self- and situation-focused cognitive strategies (Moser, Krompinger, Dietz, & Simons, 2009), open-ended reappraisal instructions (Hajcak & Nieuwenhuis, 2006), and directed reappraisals (Dennis & Hajcak, 2009; Foti & Hajcak, 2008; MacNamara, Foti, & Hajcak, 2009). The LPP can also be modulated by directing participants' attention to more or less arousing parts of complex emotional pictures (Dunning & Hajcak, 2009; Hajcak, Dunning, & Foti, 2009). Similar effects have been documented in the one published study of emotion regulation and the LPP in children (aged 5–10) (Dennis & Hajcak, 2009), although recent research (DeCicco, Solomon, & Dennis, 2012) suggests that children at the younger end of this age range, aged 5–6, are not able to successfully modulate the LPP using directed reappraisals. Taken together, these studies explore a range of cognitive emotion regulation strategies, and suggest that the effects of top-down control of attention and affective significance occur extremely rapidly, within several hundred milliseconds. The temporal resolution of fMRI is significantly slower, identifying processes that begin around one second post-stimulus or response.

NEURODEVELOPMENT AND EMOTION REGULATION

Before reviewing developmental neuroscience studies of emotion regulation, it is important to consider how brain maturation and behavioral development may influence how emotion regulation

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is evidenced in brain and behavior. In this section, we describe current findings on structural and functional brain changes in childhood that are thought to relate to the development of emotion regulatory capacities.

Compared to the ventral system, the dorsal system has a protracted developmental course (Casey, Getz, & Galvan, 2008). Because this system is relatively slow developing, there is a high degree of variability that can be expected in links between the functioning of these structures and emotion regulation behaviors over the course of development. Indeed, there appears to be low stability in childhood in the use of emotion regulation strategies that require cognitively sophisticated processes such as reappraisal (e.g., Grolnick, Bridges, & Connell, 1996). Behaviorally, the gradual maturation of prefrontal cortical areas is evident in tasks related to effortful control, attentional control, and executive functions, which increase from early childhood through adolescence (Casey et al., 1997b; Diamond & Taylor, 1996; Enns, Brodeur, & Trick, 1998; Kochanska, Coy, & Murray, 2001).

Effortful control, the ability to inhibit prepotent responses to environmental stimuli in the pursuit of goals, is considered a core ability supporting adaptive emotion regulation (Eisenberg & Morris, 2002). Showing significant development between the ages of 3 to 5 (Diamond, 1991; Zelazo, Reznick, & Piñon, 1995), higher levels of effortful control allow children to regulate behavioral predispositions, such as approach and avoidance, in order to meet goals and follow rules and expectations. However, recent work suggests that the impact of effortful control on emotion regulation differs depending on other characteristics like temperamental exuberance (Dennis, Hong, & Solomon, 2010) and that in some at-risk groups the linear development of effortful control may be disrupted (Dennis, Brotman, Huang, & Gouley, 2007).

Like effortful control, attentional control capacities develop over the course of childhood (Rothbart & Bates, 1998). They include the ability to maintain vigilance, effortfully disengage attention once it is focused, and flexibly shift attention in space (Rothbart, Posner, & Hershey, 1995). Links between attentional control and emotion regulation have been documented as early as infancy. For example, infants show decreased distress to unpleasant emotional contexts when they also show high levels of attentional control (Bell & Wolfe, 2004; Fox & Calkins, 2003). Caregivers of young infants often use attention, such as by engaging or distracting infants' attention, to help manage infants' emotions (e.g., Harman, Rothbart, & Posner, 1997). Improvements in emotional and self-regulation co-occur with developments in children's independent attentional control abilities (Kopp, 1982).

Executive functions represent some of the key processes that underlie children's increasingly sophisticated attempts to regulate emotion (Zelazo, Müller, Frye, & Marcovitch, 2003). Growing capacities for planning, working memory, and self-reflection allow for the emergence of cognitive emotion regulation in childhood and adolescence (e.g., Thompson & Goodman, 2010). As children move through the preschool period, more sophisticated anticipation and understanding of social interactions allow them to develop a range of strategies that can flexibly change across contexts. In addition, more complex information-processing skills allow for the greater identification, interpretation, and cognitive transformations that allow individuals to generate emotion regulation strategies in more creative and independent ways (Garber, Braafladt, & Zeman, 1991; Gross & Thompson, 2007).

These behavioral changes co-occur with important neural changes (Casey, Giedd, & Thomas, 2000; van der Molen, 2000). Following a brief period of synaptogenesis (until about 2 years of age), the PFC undergoes synaptic pruning and maturation of remaining synapses (Huttenlocher, 1979; Huttenlocher & Dobholkar, 1997) along with progressive myelination (Paus et al., 1999) through adolescence. While performing inhibition tasks such as a Go/No-Go task, adults compared to children show *less* activation of prefrontal regions (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002), suggesting increasing processing specificity and neural efficiency with age (Durston & Casey, 2006). This is consistent with the view that greater cognitive capacity coincides with gradual loss of synapses along with an apparent strengthening of remaining synaptic connections (Casey et al., 2000; Huttenlocher, 1990). The PFC receives input from the amygdala and striatum, and in turn modulates both structures. The extended course of development of the PFC may thus be influenced by bottom-up processes (via the amygdala and striatum) and affect top-down regulation of emotion and behavior. The ACC shows similar anatomical and functional maturation with age, including changes in volume that correlate with response inhibition performance (Casey et al., 2000; Casey et al., 1997a) as well as changes in the amplitudes of neurophysiological responses related to action monitoring and inhibitory control functions of the ACC, suggesting increased efficiency (Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006b; Segalowitz & Davies, 2004). Taken together, these studies suggest that ongoing maturation of the frontal cortex increases the efficiency with which higher order control processes are engaged.

Developmental considerations related to the function of limbic structures like the amygdala are also important to examine. The development of social avoidance behaviors is vulnerable to amygdala damage during early developmental periods (Shaw et al., 2004), while innate fear response are not (Kalin, Shelton, Davidson, & Kelley, 2001; Prather et al., 2001). Such functional impairments can have a bottom-up influence on regulatory behavior via changes in cortico-limbic connectivity. For example, differences in bottom-up processing of motivational stimuli can affect goal-directed behavior if connectivity with subdivisions of the amygdala develops differentially. Thus, to understand brain development in relation to emotion regulation, there is a need to examine patterns of connectivity among the ventral and dorsal systems.

Consistent with this perspective, Somerville and Casey (2010) present a model in which the linear development of the PFC in conjunction with an inverted U-shaped pattern of development of the striatum is directly related to changes in the ability to regulate goal-directed and affectively charged behavior over the course of childhood and adolescence. That is, linear development of the PFC supports the steady development of top-down cognitive control process (Davidson, Amso, Anderson, & Diamond, 2006), whereas striatal development, which supports the bottom-up detection of salient environmental stimuli (e.g., novel or rewarding cues), exerts a stronger influence on cognition in adolescents relative to children and adults (Figner, Mackinlay, Wilkening, & Weber, 2009). Moreover, in children, the PFC and striatum have functionally immature connections. By adulthood, the connectivity from the PFC to the striatum is mature, allowing for more appropriate and flexible top-down control of behavior under motivational demands (such as reward). During adolescence, however, when individuals are faced with many adult-like choices and challenges, the influence of the striatum on the PFC (i.e., the influence of motivation on cognition) is at a peak. Thus, adolescence is a time in which enhanced sensitivity to incentives has a bottom-up influence on cognitive control.

Ernst and Fudge's (2009) "triadic model" provides a complementary perspective on the Somerville and Casey model (2010). The "triadic model" proposes that motivated behavior emerges out of the mutual regulation among approach, avoidance, and regulatory systems, each of which has distinct but overlapping neural circuits. In addition to the PFC and striatum, this model includes the amygdala as another node in the functional connectivity of the motivation–cognition systems. The mature motivated behavior system in adults is represented by a balance between ventral striatum (approach) and amygdala (avoidance) function, with relatively equal cortical control exerted by the PFC (regulatory) on each. In adolescents, the approach–avoidance balance is biased toward the striatum, or approach behaviors, reflected by enhanced reward sensitivity and risk taking in adolescents. Development of the functional connectivity between the striatum, amygdala, and PFC, rather than the individual influence of a single brain area, underlies the triadic model as well. Thus, it is the maturation of each of these areas in concert that underlies the development of motivated behavior.

A growing number of studies have also begun to examine neurodevelopment in relation to individual differences in affective psychopathology. Along with a significant body of research on emotion regulation and adult psychopathology (e.g., Hamann & Canli, 2004; Kring & Sloan, 2010; Urry et al., 2006), a full discussion of the developmental literature is beyond the scope of this chapter (see Adrian, Zeman, & Veits, 2011; Cole, Mischel, & Teti, 1994). Instead, we briefly review some new findings on neurobiological changes and the emergence of psychiatric disorders in adolescence (see also Ladouceur, Peper, Crone & Dahl, 2012; Paus, Keshavan, & Giedd, 2008).

Consistent with Ernst and Fudge's (2009) and Somerville and Casey's (2010) models of neurobiological maturation and emotional development during adolescence, the combination of strong affective drives and immature prefrontal development may in part explain why the peak age of onset for many psychiatric disorders is adolescence (Paus et al., 2008). Indeed, along with important neurodevelopmental (Giedd et al., 1999; Luna, Padmanabhan, & O'Hearn, 2011; Peper et al., 2008) and hormonal changes (Schulz, Molenda-Figueira, & Sisk, 2009; Spear, 2010), adolescence is characterized by a sharp increases in the incidence of problems related to emotional and behavioral regulation, including those related to risk taking and sensation seeking, such as accidents, alcohol and drug use, and emotional disruptions (Centers for Disease Control and Prevention, 2009). In both humans and animals, puberty may be a sensitive period for the influence of reproductive hormones on the organization of the brain (e.g., Chowen, Azcoitia, Cardona-Gomez, & Garcia-Segura, 2000; Cunningham, Claiborne, & McGinnis, 2007; Sarkey, Azcoitia, Garcia-Segura, Garcia-Ovejero, & DonCarlos, 2008; Schulz et al., 2009; Yates & Juraska, 2008), and this influence may play a key role in the emergence of these types of psychopathology (Paus, 2008). For example, a recent review explores the influence of puberty on white matter development, and highlights the role of this development in relation to the neural systems underlying emotion and behavior regulation as well as risk for affective disorders (Ladouceur et al., 2012).

White matter tracts, consisting of myelin-coated axons, facilitate communication among neural regions and thus provide the infrastructure for neural networks. Both cortico-cortico as well as cortico-subcortical networks underlie emotion regulatory functions. Thus, by targeting the development of white matter, researchers can track a key mechanism underlying patterns of brain connectivity that allow efficient emotion regulatory functions to operate. In their review, Ladouceur and colleagues (2012) show that puberty represents a time of unique influence on white matter development. For example, boys and girls differ in the timing of white matter development, myelination, and organization—with a trend for some white matter tracks, like the splenium of the corpus callosum (e.g., Silveri et al., 2006), to organize faster in females than males. This and other gender differences may be due to the earlier onset of puberty in females (Styne & Grumbach, 2002).

These differences are particularly important in light of recent evidence showing that the microstructure of white matter differs in adults diagnosed with affective disorders (e.g., Sexton, Mackay, & Ebmeier, 2009; Versace et al., 2008; Zhu et al., 2011) and in youth at risk for such disorders (Huang, Fan, Williamson, & Rao, 2011; Versace et al., 2010). Moreover, disruptions in cortico-limbic networks are clearly implicated in affective psychopathology (Mayberg, 2001; Savitz & Drevets, 2009) and thus puberty-specific influences on white matter development are likely to have an important impact on the integrity of this neural circuitry. Indeed, one study showed lower fractional anisotropy (suggesting reduced myelination and structural integrity) in several white matter tracts in healthy adolescents at high familial risk for unipolar depression compared to healthy controls (Huang et al., 2011). These and other suggestive findings lead Ladouceur and colleagues (2012) to hypothesize that changes in several key areas, including the splenium of the corpus callosum and the uncinate fasciculus, which connects three key regions involved in emotion regulation (i.e., amygdala, lateral and medial prefrontal cortex; Highley, Walker, Esiri, Crow, & Harrison, 2002), may represent a potential vulnerability marker for future onset of affective disorders in high-risk youth. This small but growing body of research has the potential to identify a range of neurobiological factors that could subserve both adaptive and maladaptive emotion regulation.

NEURODEVELOPMENT AND ERPs

The ERP literature has focused on tracking developmental changes in activity of the ACC, given its central role in self- and emotion regulation and in the integration between emotion and cognition. These include the N2, error-related negativity (ERN), and error positivity (Pe) (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993; van Veen & Carter, 2002a, 2002b; Yeung, Botvinick, & Cohen, 2004). These components are maximally distributed at fronto-central sites and have neural generators in the dorsal region of the ACC (e.g., Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004; van Veen & Carter, 2002a, 2002b; Yeung et al., 2004). These components are thought to reflect distinct yet closely related cognitive control processes, each of which plays a crucial role in self-regulation.

The N2 occurs over the frontal midline regions 200 to 350 ms following a response or stimulus, and is generated by the dorsal region of the ACC (Gehring & Willoughby, 2002; van Veen & Carter, 2002a, 200b). In contexts in which participants are asked to inhibit a response (such as Go/No-Go tasks), the N2 reflects successful inhibition of a prepotent response (Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003). When the N2 is synchronized to a stimulus, it reflects conflict and action monitoring (Luu, Flaisch, & Tucker, 2000; Nieuwenhuis et al., 2003); that is, it is implicated in tasks requiring monitoring of "crosstalk," or conflicting information or response options, and is thought to signal the extent to which attentional control is required (Barch, Braver, Sabb, & Noll, 2000; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). In children, the posterior N2 may also reflect this inhibitory function (Ciesielski, Harris, & Cofer, 2004), perhaps due to immature frontal-parietal networks that subserve cognitive control. The anterior N2, however, is also identifiable in early childhood (Buss, Dennis, Brooker, & Sippel, 2011).

The ERN and Pe may capture distinct aspects error monitoring. The ERN is observed at frontal-central recording sites and peaks around 50 to 100 ms after an error is made. The ERN is thought to reflect the relatively early and automatic detection of conflict and mismatch: mismatch between the actual error and the expected correct responses (Falkenstein et al., 1991), or detection of conflict between the error response with the simultaneous but incompatible representation of the correct response (van Veen & Carter, 2002a). Like the ERN, the Pe is detectable in frontal-central recording sites, but has a slightly more posterior scalp distribution. The Pe follows the ERN and typically peaks between 200 to 400 ms after an error is made (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Much less is known about the Pe, which may reflect relatively later and more elaborated and conscious detection of an error having been made (Endrass, Reuter, & Kathmann, 2007; Leuthold & Sommer, 1999; Nieuwenhuis et al., 2001; O'Connell et al., 2007), although there continues to be debate about the specific role of the Pe in error detection (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). One suggestion is that the Pe indexes error recognition and error salience processing (Nieuwenhuis et al., 2001). The output of these error detection systems may guide emotion regulation by marking the cognitive and emotional significance of a deviation from an anticipated response (Gehring et al., 1993).

Developmental studies have demonstrated that these components can be detected even in children of preschool age (e.g., Brooker, Buss, & Dennis, 2011) and that these components undergo similar developmental changes in childhood and adolescence, such that by mid- to late adolescence, amplitudes increase to reach adult-like levels (Davies, Segalowitz, & Gavin, 2004; Ladouceur, Dahl, & Carter, 2004; 2007). Not all changes are linear, however. For example, in a study of 7- to 25-year-olds, there was a clear reduction, rather than increase, in the ERN between the ages of 10 to 13 with subsequent fluctuations during adolescence. The authors interpreted this to reflect neuromodulatory changes, particularly in the mesencephalic dopamine system (Holroyd & Coles, 2002), that occur at the onset of adolescence. Moreover, the Pe was robust throughout the age range, suggesting relatively little maturation. This is consistent with dipole models suggesting that the Pe may be generated in part by more posterior brain regions (van Veen & Carter, 2002a) which would undergo more rapid developmental change in childhood compared to the prefrontal cortex.

Although little research has directly examined these ERPs in relation to child emotion regulation, several lines of research may be relevant. First, research on error-related components during emotional contexts suggests that error and conflict detection serve to guide the inhibition of behavior and flexible delegation of attention (Lewis & Stieben, 2004; Luu & Tucker, 2004), and that this varies

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DEVELOPMENTAL NEUROSCI

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EMOTION REGULATION STRATEGIES

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with emotional and motivational context (Luu, Tucker, Derryberry, Reed, & Poulsen, 2003; Tucker, Hartry-Speiser, McDougal, Luu, & deGrandpre, 1999). Second, changes in amplitude of these components are associated with problems in emotion regulation. For example, decreased amplitudes of ERN and N2 are found in dysthymia (Yee, Deldin, & Miller, 1992), aggression (Dikman & Allen, 2000), and childhood attention-deficit/hyperactivity disorder, suggesting difficulty initiating or maintaining response inhibition (Pliszka, Liotti, & Woldorff, 2000; Yong-Liang et al., 2000). Yet, such reductions are also found following administration of anxiety-reducing drugs (Johannes, Wieringa, Nager, Dengler, & Münte, 2001). At the same time, increased amplitudes of N2 and ERN are linked to the need to expend greater cognitive resources during cognitive control tasks and thus reflect reduced neural efficiency. For example, children who are younger or who show internalizing symptoms show larger N2 and ERN waveforms during a Go/No-Go task with failure feedback (Lewis & Stieben, 2004). A recent study further documented that greater N2 amplitudes were associated with less efficient executive attention and lower temperamental effortful control (Buss et al., 2011). Furthermore, increased amplitudes of ERN have been observed in individuals diagnosed with obsessive–compulsive disorder (Gehring, Himle, & Nisenson, 2000; Hajcak & Simons, 2002) and in those with high trait negativity (Luu, Collins, & Tucker, 2000). Thus, depending on a child's age or the particular regulatory disruption, increased *or* decreased ERPs linked to the recruitment of cognitive control may reflect difficulties with emotion regulation (Brooker et al., 2011).

DEVELOPMENTAL NEUROSCIENCE STUDIES OF EMOTION REGULATION

In the following section, we review the small but growing developmental neuroscience literature on emotion regulation in three broad categories: the study of emotion regulation strategies; how cognitive processes change under emotional demands; and, although almost no published neuroscience studies exist to date, social factors influencing child emotion regulation. While there are surprisingly few studies that directly target neural correlates of emotion regulation in children, what exists currently already points to exciting opportunities to strengthen measurement approaches and to identify cutting-edge questions about emotion regulation. At the same time, we will highlight how neuroscience studies can greatly benefit from careful consideration of the behavioral science literature on the development of emotion regulation.

Emotion Regulation Strategies

Very few studies have examined the use of discrete emotion regulation strategies in young children from a neuroscience perspective. From a behavioral perspective, there are important developmental shifts in the expression and regulation of emotion. In infancy, emotional reactivity is more global, with increasingly differentiated vocal, facial, and postural cues of emotion in early and middle childhood (Camras, Malatesta, & Izard, 1991). Children's early attempts at emotion regulation, although primitive, are already effective by the first months of life (Buss & Goldsmith, 1998; Calkins, Dedmon, Gill, Lomax, & Johnson, 2002). Newborns can respond to aversive experiences in the environment with basic withdrawal responses, such as gaze aversion, and with early self-soothing behaviors, such as sucking, that show some effectiveness in reducing arousal. For example, in a study of 6- to 18-month-olds (Buss & Goldsmith, 1998), the use of distraction and approach behaviors reduced the expression of anger during emotional challenges, but were less effective in reducing fear. With ongoing neural development and increasing cognitive sophistication, emotion regulation strategies shift from being relatively external (i.e., caregiver supported) and behaviorally focused to more cognitive and internally focused (Kopp, 1989), including cognitive emotion regulation.

Very few studies have examined the use of specific emotion regulation strategies in children from a neuroscience perspective. To our knowledge, one published neuroimaging study and one published ERP study have studied the neural underpinnings of a specific strategy, reappraisal. Lévesque and colleagues (Lévesque, Joanette, Mensour, Beaudoin, Leroux, & Beauregard, 2004) examined 8- to 12-year-old girls, finding that reappraisal in response to sad stimuli was associated with regions similar to those documented in adults— the lateral PFC and MPFC, as well as the right ACC and vLPFC. In a study from our lab (Dennis & Hajcak, 2009), we examined the LPP in children during a directed reappraisal task. We found that unpleasant emotional pictures (developmentally appropriate pictures from the International Affective Pictures System; Lang, Bradley, & Cuthbert, 2008) that were described in neutral compared to negative terms elicited smaller LPPs in 5- to 10-year-old children, suggesting that reappraisal was effective in reducing the emotional salience of the picture. This effect was evidenced at later latencies than previously shown in adults (Hajcak & Nieuwenhuis, 2006), suggesting developmental shifts in the timing of cognitive emotion regulation processes. In addition, greater modulation of the LPP by neutral interpretations was associated with fewer symptoms of anxiety and depression, whereas larger LPP amplitudes were associated with greater mood symptoms and disruptions in emotion regulation. This suggests that the ability to use cognitive emotion regulation strategies is disrupted by anxiety and depression symptoms and that increased processing of unpleasant emotional stimuli in an emotion regulation context may be a marker for decreases in emotional well-being. There were additional age and gender effects, such that younger girls (aged 5–6) did not show expected down-regulation of the LPP via reappraisal. Indeed, in a follow-up study (DeCicco et al., 2012), we found that when the age range is restricted to 5 to 6 years of age, directed reappraisal was not effective in reducing LPP amplitudes to unpleasant emotional pictures. However, larger LPP amplitudes to unpleasant compared to neutral pictures (in both the negative and neutral interpretation contexts) was associated with increased symptoms of

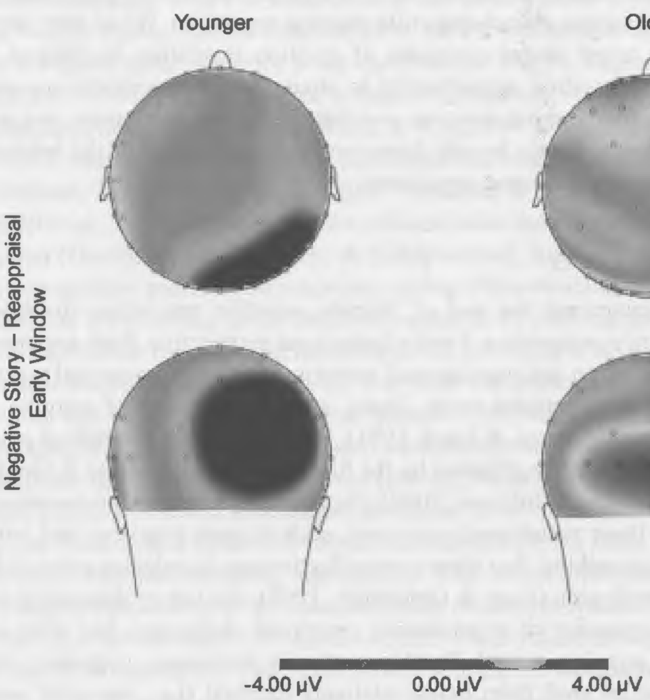

FIGURE 8.1 Effects of reappraisal on the LPP. Eight- and 9-year-olds (older), but not 7-year-olds (younger), showed an adult-like effect of reappraisal on the LPP (reduced LPP amplitudes for reappraisal versus negative interpretations). The scalp distributions of the LPP difference scores (LPP negative interpretation–LPP reappraisal) are presented in posterior recording regions from 300-800 ms. Greater positivity indicates increased reduction of the LPP via reappraisal. Participants were 20 children aged 87-113 months, M = 98.20, SD = 6.05

anxiety and internalizing problems, suggesting a bias for elaborated processing of unpleasant pictures. Indeed, in an additional follow-up study with children aged 7 to 9 (DeCicco, O'Toole, & Dennis, under review), we found that 8- and 9-year-olds, but not 7-year-olds, showed an adult-like effect of reappraisal on the LPP (reduced LPP amplitudes for reappraisal versus negative interpretations; see Figure 8.1), and that the degree of this effect was associated with fewer symptoms of anxiety. This suggests that there may be critical or sensitive periods for the development and effective use of reappraisal—at least using this specific method, taken from the adult literature—and that measuring neural responses in an emotion regulation context are relevant for understanding emotional dysregulation. This may be the case even when children are able to fully employ a given cognitive strategy. It will be critical for future research to examine the boundary conditions under which children can use cognitive strategies like reappraisal, and whether by bootstrapping children's ability to understand and employ cognitive emotion regulation, we can detect effective use of these strategies in even younger children.

There is a substantial literature on asymmetric EEG activity (the difference in EEG power between left and right frontal scalp locations) in relation to emotion regulation and affective psychopathology (for reviews, see Coan & Allen, 2004; Kline & Allen, 2004). Due to space constraints, however, and because specific emotion regulation strategies are not typically measured in these studies, we will not review this rich literature in depth. In brief, EEG asymmetry is thought to reflect dispositional affective and behavioral tendencies. In a seminal study, Davidson and Fox (1989) found that resting frontal asymmetry in 10-month-old infants predicted their emotional response to maternal separation—those infants who cried and showed distress when mothers left for a short period of time had greater right frontal asymmetry than those who did not cry. More recently, Fox and colleagues (Fox, Henderson, Rubin, Calkins, & Schmidt, 2001) showed that EEG asymmetry helped explain continuity and discontinuity of temperament over the first four years of life. Those children who were consistently inhibited and stayed inhibited had greater right frontal EEG asymmetry. Children who changed from inhibited to non-inhibited did not display this pattern of brain activity. On the other hand, children who at 4 months were classified as being highly exuberant were likely to remain exuberant regardless of patterns of EEG asymmetry. These two studies suggest that baseline EEG activity may reveal important patterns of emotional and behavioral reactivity that could shape dispositional patterns of emotion regulation (Dennis & Solomon, 2010; Solomon, Hong, Klimova, Powers, & Dennis, 2010).

Cognitive Processes Under Emotional Demands

Consistent with the idea that emotions are not only regulated, but regulate other processes (Cole et al., 2004), perhaps the largest body of developmental neuroscience research on emotion regulation uses ERPs and fMRI to measure changes in cognitive processes in the context of emotional stimuli or a mood induction. This is consistent with much of the behavioral research on emotion regulation which uses emotionally challenging tasks to elicit emotions and then observe strategies or behaviors that reflect the regulation of emotion (Cole et al., 2004) or that track the time course of how expressed emotion changes as a result of a given strategy (e.g., Buss & Goldsmith, 1998). Some tasks target broad negative emotion like frustration (Dennis, 2006), others seek to elicit specific emotions such as disappointment (Cole, Zahn-Waxler, & Smith, 1994), and still others focus on the regulation of motivational drives, like delay of gratification (Mischel, Shoda, & Rodriguez, 1989).

In neuroscience contexts, the emotional context is often the presence of emotional stimuli while children perform a cognitive task. For example, in one study from our lab, we created a relatively mild emotional context by presenting distracting emotional faces to 5- to 9-year-olds during performance of an attention task (Dennis, Malone, & Chen, 2009).We examined changes in ERPs related to early attentional orienting (P1) and later attentional processing (the frontal Nc) in response to the emotional faces as children completed the children's Attention Network Test (Fan, McCandliss, Sommer, Raz, & Poser, 2002; Rueda, Posner, & Rothbart, 2005). We found that larger P1 amplitudes to fearful and sad faces were associated with better attention and fewer maternal reports of emotion dysregulation, whereas larger Nc amplitudes to fearful faces were associated with more efficient executive attention. This suggests that in this age group, the ability to recruit greater attentional resources in an emotionally distracting context, even at the stage of very early attentional orienting, is associated with reduced dispositional dysregulation and increased ability to regulate behavior in an emotional context.

Research from other labs has also used ERPs to examine how children regulate attention and cognitive resources in emotionally challenging contexts. For example, Perez-Edgar and Fox (2005) presented children with a Posner spatial cuing task under an affectively arousing condition in which children played for points and were given random, non-contingent feedback and in a traditional condition in which no points or feedback were involved. The affective versus traditional condition generated greater ERPs (only reaching significance for the N1 and the positive slow wave) suggesting that increased ERPs reflected a child's attempt to regulate their attention in the face of emotional demands. A series of ERP studies from Lewis and colleagues also suggests that the ability to recruit cognitive resources during a task in which performance demands compete with a negative mood induction—losing points during a Go/No-Go task—is related to behavior and emotion regulation (Lewis, Granic, Lamm, Zelazo, Stieben, Todd, et al., 2008; Lewis, et al., 2006b; Lewis & Stieben, 2004; Stieben et al., 2007). In a group of typically developing children, N2 amplitudes were larger after losing points compared to when they gained points, suggesting that greater cognitive resources were recruited in the emotionally evocative portion of the task (Lewis et al., 2006b). In children showing emotional and behavioral dysregulation, such as clinically elevated internalizing and externalizing problems, greater N2 amplitudes while losing points were correlated with more flexible interpersonal behavior during emotionally challenging interactions between children and their mothers (Lewis, Granic, & Lamm, 2006a). In another study (Stieben et al., 2007), children showing both internalizing and externalizing problems, compared to typical children, showed enhanced N2 amplitudes *following* point loss, whereas children showing only externalizing problems showed reduced ERN amplitudes for incorrect trials compared to control children (Stieben et al., 2007).

The latency of these responses may also reflect important affective individual differences. In one study (Lewis, Todd, & Honsberger, 2007), 4- to 6-year-olds viewed angry, neutral, and happy faces in an emotional Go/No-Go task. The frontal N2 in response to emotional faces was interpreted as reflecting effortful attention or response control recruited in an emotional conflict context. Results showed that shorter N2 latencies to angry faces were associated with more temperamental fear, suggesting that more rapid recruitment of attentional resources could reflect the fearful child's need to regulate anxiety during stimulus appraisal and processing—a step which would precede subsequent efforts at emotion regulation. Overall, these studies suggest that the ability to recruit cognitive control under emotionally demanding conditions may reflect a core regulatory capacity that tends to be greater among typically developing children compared to those showing developmental disruptions. These studies also suggest that the excellent temporal resolution of ERPs combined with their relative ease of administration with children, compared to fMRI, make ERPs a highly sensitive measure of emotion regulatory processes.

Future research could also use fMRI to examine similar questions, and can better isolate neural circuitry underlying effects. A recent study using a version of Lewis and colleagues (2006b) Go/No-Go task modified for the fMRI scanner (Perlman & Pelphrey, 2011) found that 5- to 11-year-olds and adults displayed distinct patterns of ACC and amygdala activation during emotion regulation episodes (point loss during a Go/No-Go task). Specifically, they found that adults showed increased amygdala activation during the emotion regulation recovery period, but children showed decreased amygdala activity during this time. Moreover, connectivity analyses showed that as emotion regulation demands increased, the effective connectivity between the ACC and amygdala also increased, and that such patterns of connectivity increased with age.

In another fMRI study with children, Hare and colleagues (Hare, Tottenham, Galvan, Voss, Glover, & Casey, 2008) examined whether difficulties in the ability to regulate behavior in emotional contexts (an emotional Go/No-Go paradigm) was related to competition between subcortical emotional processing centers and immature prefrontal systems. This study include children (aged 7–12), adolescents (aged 13–18), and adults (aged 19–32). Results showed that adolescents showed exaggerated amygdala activity relative to children and adults, a difference that decreased with repeated exposure. Interestingly, self-report of trait anxiety predicted the degree of this habituation in the amygdala—greater trait anxiety was associated with reduced habituation. Reduced habituation was in turn associated with less functional connectivity between vPFC and amygdala. These results suggest that exaggerated emotional reactivity creates a greater need for top-down control of emotional processing, so that individuals with less control could be at risk for poor outcomes. The examination of emotion regulation in terms of cognitive performance under emotional demands will be an important tool for future neuroscience studies examining the development of emotion regulation and related processes (Tottenham, Hare, & Casey, 2011).

Some recent ERP studies of emotion regulation highlight the critical role of individual differences: that is, that the meaning of a particular brain response in relation to regulatory behavior will differ depending on the individual difference. For example, Henderson (2010) examined typically developing children performing a modified flanker task. The N2, an ERP thought to reflect activity of the ACC and conflict monitoring, was measured during the flanker task. Greater child shyness was associated with poorer social-emotional outcomes primarily among children with relatively enhanced N2 amplitudes. This suggests that patterns of action monitoring as measured by ERPs may be an important moderator of risk (e.g., shyness) for disrupted adjustment. Consistent with this idea, we measured the N2 during a flanker task in a group of adults varying in trait anxiety (Dennis & Chen, 2009). In this task, each trial of the flanker task was preceded by threat-relevant (fear) or non-threat-relevant (sad, happy, and neutral) emotional distracters. We found that high trait anxiety was associated with larger N2 amplitudes during congruent (low conflict) trials following fearful faces, which suggests excessive conflict monitoring in a threat-relevant context. Moreover, those high trait anxious participants who showed the largest N2 amplitudes showed the worst attention performance. In this study, as in the study by Henderson (2010), it was the interplay between affective style and neural responses related to conflict monitoring, rather than each individually, that explained the most variance in outcomes.

Social Factors and Emotion Regulation

Although the field of social neuroscience and even the neuroscience of attachment has made headway in examining social factors impacting emotion regulation and stress reactivity (Coan, 2008), this research has been almost exclusively conducted with adults. To our knowledge, little or no published research has examined the impact of parenting or other social factors on neural processes underlying emotion regulation. In data from our lab (Kessel, Huselid, DeCicco, & Dennis, under review), we attempted to examine the interplay between parenting and emotion regulation by testing whether the LPP and parenting interact to predict child fearful behavior. We found that children showing a bias towards unpleasant stimuli (larger LPP amplitudes to unpleasant versus neutral stimuli) were more fearful during an emotional challenge, but only when parents showed low levels of "promotion parenting" which involves parents focusing their children on approaching and obtaining positive, rewarding outcomes. Thus, the fit between children's neural responses to unpleasant emotion and a parent's ability to focus children on positive outcomes together predicted the regulation of fear.

Although not directly targeting how parenting shapes neural processes underlying emotion regulation, an interesting body of research assesses parenting in relation to affective psychopathology (Silk et al., 2007). For example, Forbes and colleagues (Forbes, Fox, Cohn, Galles, & Kovacs, 2006) found that for children of parents with a childhood history of depression, greater left frontal EEG activity was related to internalizing and externalizing problems, suggesting a link between parenting and physiological responses associated with affect regulation in children. Given the strong emphasis placed on the role of socialization and parenting in behavioral emotion regulation research, neuroscience research on this topic is an extremely exciting and open area of research.

EMOTION REGULATION AND THE AGING BRAIN

At the other end of the developmental spectrum, very little is known about emotion regulation in older adults. Although aging is associated with a cognitive and physical decline, older adults may show improvements in some areas related to emotion regulation. For example, the Socioemotional Selectivity Theory (SST) suggests that older adults are more adept at regulating emotions because of the perception that they have less time left in life and become increasingly motivated to focus more on positive rather than negative emotional events (Carstensen, Fung, & Charles, 2003). If this is correct, then older versus younger adults should be able to more easily reduce negative emotions and promote positive emotions. In fact, older adults report experiencing less negative affect than their younger counterparts (Stawski, Almeida, Sliwinski, & Smyth, 2008) and feel more in control of their emotions (Gross et al., 1997). Other cognitive processes may also be influenced by these age-related changes, such as memory. Described as the positivity effect, older adults show a bias for remembering positive emotional information, as compared to younger adults who remember more negative emotional information (Carstensen et al., 2003; Mather & Carstensen, 2005; Scheibe & Carstensen, 2010).

Despite these early findings, research in neuroimaging suggests that older adults are not more successful at using cognitive reappraisal to reduce negative emotions (Opitz et al., 2012). In a gaze-directed cognitive reappraisal task, older adults showed reduced activation of key regions of the prefrontal cortex (dorsomedial and left ventrolateral) known to facilitate the use of reappraisal strategies (e.g., Ochsner et al., 2004). Younger versus older adults in this same study were somewhat better at using cognitive reappraisal strategies, and older adults were better at increasing versus decreasing emotional responses to unpleasant stimuli. Consequently, older adults also rated trials in which they were instructed to decrease emotional responses as more intense than a baseline condition. Other studies have demonstrated similar results, where older adults have increased activation of PFC regions (ventral lateral, dorsolateral, and dorsomedial regions) and the amygdala when increasing emotional responses to unpleasant stimuli, but not on trials when asked to decrease emotional responses. Interestingly, a subset of older individuals who showed increased ventral medial PFC activation and reduced amygdala activation in the decrease condition also had reductions in cortisol (Urry et al., 2006). In a follow-up study, van Reekum and colleagues (2007) found predicted reductions in both amygdalae when older adults were asked to decrease emotions. Moreover, directions to increase emotions resulted in the greatest PFC activation followed by the decrease condition and baseline conditions respectively.

Neural correlates of these biases in older adults have only recently been examined using the late positive potential (LPP). If a bias towards positive stimuli truly exists in older adults, LPP amplitudes should be larger to pleasant versus unpleasant and neutral stimuli compared to younger adults. Studies show mixed results in reference to this hypothesis. When older and younger adults passively view emotional stimuli, LPP amplitudes are larger to pleasant versus unpleasant stimuli in older adults and larger to pleasant versus unpleasant stimuli in younger adults, but no significant age effects emerge (Langeslag & van Strien, 2009). However, another study showed that older adults had reduced LPP amplitudes to both pleasant and unpleasant versus neutral stimuli (Wood & Kisley, 2006), and another study showed that amplitudes to unpleasant stimuli alone were reduced with age (Kisley, Wood, & Burrows, 2007). This small body of literature has also documented that LPP amplitudes do not differ between younger and older adults when asked to increase and decrease emotional responses to unpleasant stimuli (Langeslag & van Strien, 2010). Although results hold promise for using the LPP to identify neural correlates of emotional processing regulation in older adulthood, results are mixed and document more within group rather than between group differences.

Taken together, these studies suggest that older adults may process emotional information differently than their younger counterparts, including increased focus on positive emotion, but have greater difficulty recruiting areas of the PFC to down regulate negative emotions. The Selective Optimization and Compensation model of Emotion Regulation (SOC-ER; Urry & Gross, 2010) has attempted to integrate these findings. The model posits that older adults may compensate for a loss in cognitive control by selecting situations in which they can focus more on positive emotions (Urry & Gross, 2010). The SOC-ER model suggests that older adults are encouraged by a smaller circle of friends and family to become engaged in positive situations (Carstensen et al., 2003), which allows them to select situations that are more positive, to compensate for a loss in resources related to cognitive control. This may partially explain why older adults report experiencing more control over their emotions in addition to using more reappraisal strategies, despite reduced activity in the PFC. In contrast, younger adults may be able to use cognitive control processes to employ reappraisal strategies with less effort than older adults. As a result, younger versus older adults are less likely to use a situation selection method to compensate for low cognitive control resources. This suggests that older adults may focus on more positive emotional information and events because they outwardly select them rather than being able to use reappraisal as an effective strategy in reducing negative emotion. While the SOC-ER model is only suggestive of how reappraisal strategies may operate in younger and older adults, it provides a framework for future research on emotion regulation and aging.

NEVER THE TWAIN SHALL MEET? BRINGING BRAIN AND BEHAVIOR BACK TOGETHER

Many critical areas of inquiry that are central to behavioral research on emotion regulation are not even touched on in the developmental neuroscience literature, and vice versa. Is the gulf between the fields too wide? In this current environment of neuro-enthusiasm following the "Decade of the Brain," will behavioral science become the red-headed stepchild of neuroscience? We hope not, and believe that interdisciplinary researchers must seek out and advocate for a much stronger interaction between the two fields. In the following, we highlight opportunities for such interactions in the domain of three concepts in emotion regulation research: interactions between reactivity and control, development, and social-contextual factors. Although space limitations prevent us from a thorough review of the large behavioral literature on emotion regulation, we refer readers to several other sources (e.g. Cole, Dennis, Smith-Simon, & Cohen, 2008; Cole, Martin, & Dennis, 2004; Thompson & Goodman, 2010).

Interactions Between Reactivity and Control

Although the neuroscience literature clearly highlights the interplay between neural regions related to emotional functions and cognitive control functions, few if any neuroscience studies have actually tested how regulation of mood and behavior emerges out of the *interplay* between reactive and control processes (Dennis, 2010; Henderson, 2010; Henderson & Wachs, 2007). That is, questions remain about how reactive processes actually influence control processes and how control processes over time shape the nature of reactivity. Instead, research tends to focus on one, albeit important, "see-saw" pattern in which a pattern of increased activity in control centers (e.g., PFC, dACC) is inversely related to activity in emotional centers (e.g., amygdala, rACC, insula) during emotion regulation—a pattern that is disrupted in psychopathology (e.g., depression and anxiety).

Because both reactive and regulatory processes have been conceptualized as temperamental traits (early appearing and relatively stable over development), temperament and developmental researchers have contributed to our understanding of reactive and control processes in emotion regulation (e.g., Derryberry & Rothbart, 1997; Fox, 1994; Rothbart, Derryberry, & Hershey, 2000; Silk et al., 2007). For example, in a seminal paper on this topic, Derryberry and Rothbart (1997) discuss the organization of temperament in terms of reactive and control processes. They articulate the importance of examining the reciprocal influences within temperament systems: For example, as cortical representations develop, they provide more mature feedback to motivational systems thus enhancing and refining detection and guidance capabilities. While these are normative neural processes, it is at the level of these reciprocal influences that dysregulation might occur. For example, anxiety may be linked to faulty feedback to motivational systems leading to exaggerated threat detection in children with fearful temperament, while impulsivity may be linked to enhanced salience of reward pathways in approach-oriented children. At the same time, problems with anxiety are also linked to between-system interactions, such as between motivational and attentional systems. For example, approach motivation is regulated via reactive attentional processes related to fear as well as by effortful control of attention. It is suggested that two types of psychopathology, anxious and impulsive psychopathology, can be examined in terms of problems in these dual means of control, leading to either overregulation or underregulation.

Derryberry and Rothbart (1997) wrote this wonderful theoretical paper well over a decade ago at the writing of this chapter. While it has had a broad impact on how temperament and psychopathology are conceptualized, research directly testing these types of hypotheses is still in its infancy. In a pilot study inspired by this viewpoint (Solomon, Hong, & Dennis, 2011), we examined whether the ability to recruit cognitive resources for conflict monitoring, measured via the N2 while 5- to 6-year-old children completed a flanker task with emotional distracters, was related to maternal report of emotion regulation. This attention task required that children ignore salient emotional stimuli and maintain attention to the task. Critically, we tested whether effects differed for children varying in temperamental exuberance, which is characterized by high sensitivity to rewards and positive emotionality. Exuberance, because of strong drives for rewards, may create risk for dysregulated approach behaviors and difficulties with emotion regulation, particularly in incentive contexts. We found that relatively high exuberance was associated with greater emotion dysregulation, but only when N2 scores were increased following happy faces. This suggests that increased conflict monitoring in the context of reward-relevant emotional stimuli (happy faces) may reflect difficulties in regulating approach drives (i.e., children have to expend more resources or neural effort to ignore distracting reward signals in order to maintain task performance), but only for those children who are behaviorally sensitive to reward. Results also highlight that whether a given cognitive response is adaptive or maladaptive may be best understood in the context of an individual's affective and motivational characteristics.

When considering the role of reactivity, it is also critical to consider that negative emotions do not uniformly have a disruptive impact on adjustment, and instead are fundamentally adaptive if well-regulated (Campos, Campos, & Barrett, 1989; Frijda, 1986). Negative emotions can facilitate cognitive processes, attention, and learning, making them adaptive under some conditions (Barrett & Campos, 1987; Carver, 2004; Kanske & Kotz, 2010; Pessoa, 2009). For example, in a study with typically developing children, expressions of anger were temporally associated with increased use of adaptive and context-appropriate actions during emotional challenges (Dennis et al., 2009). This idea that emotions serve adaptive, organizing behavioral functions tends to be overlooked, despite the fact that functional emotion theory has been embraced by many scholars (Campos et al., 1989).

In summary, temperament researchers have begun to examine the interplay between reactive and control processes in relation to emotion regulation. Neuroscience researchers are in the unique position of having highly sensitive tools with which to delineate patterns of neural activity associated with both positive and negative emotional reactivity and control processes that may shape the development of emotion regulation.

Development

Conducting truly developmental research on emotion regulation is difficult to say the least. Such work must track continuity and discontinuity in emotion regulation over time, mechanisms of change and stability, factors that influence the trajectory of the links between emotion regulation and adjustment over the lifespan, and meaningful comparisons between children and adults. Yet, if using the tools of neuroscience is to significantly contribute to our understanding of how emotion regulation develops and how it in turn impacts adjustment, this is exactly the challenge to which developmental neuroscientists must rise. To our knowledge, there is no neuroscience research directly examining how emotion regulation develops and patterns of change and stability, although research with a cross-sectional design begins to get at such questions (e.g., Hare et al., 2008).

The behavioral literature highlights several important developmental issues related to emotion regulation. Although emotion regulation tends to improve over childhood (Graziano, Keane, & Calkins, 2010), such development is likely non-linear due to a broad array of changes in neural circuitry underlying motivational and control processes and their interplay during childhood and adolescence (Ernst & Fudge, 2009; Somerville & Casey, 2010). Indeed, the field of developmental psychopathology emphasizes the importance of taking an organizational rather than linear perspective on the development of emotion regulation (Cicchetti, Ganiban, & Barnett, 1991; Cicchetti & Toth, 1998). Organizational models posit that development proceeds in predictable stages in which each developmental stage presents new challenges, called stage-salient tasks. At times of transition between stages, greater disorganization will likely emerge, followed again by a period of integration and relative stability. Adequate resolution of these tasks supports the development of competence and superior adaptive skills, and inadequate resolution does the opposite. The earlier the stage during which difficulties emerge, the greater the chances that subsequent stages will also show disruptions.

Recent research has also detected age-related shifts in children's cognitive understanding of emotion regulation that may predict emotion regulation behavior. For example, 4- versus 3-year-olds are better at identifying emotion regulation strategies relevant to anger, and this ability predicted more observed emotion regulatory competence (Cole et al., 2008). A study comparing 3- to 5-year-olds with college adults found that while children as young as 3 years can identify effective emotion regulation strategies similar to those selected by adults (e.g., distraction), they also show a preference for ineffective strategies (e.g., venting; Dennis & Kelemen, 2009). Those children endorsing more ineffective strategies, particularly venting, were rated by mothers as having lower social skills. Although these are promising early findings, no studies have tracked children's understanding of emotion regulation using a longitudinal design.

A developmental perspective on emotion regulation also must be concerned with how styles of emotion regulation emerge (Davidson, 2000; Gross, 1998b; Sroufe, 1995). This requires a consideration of emotion–behavior sequences (Dennis et al., 2009) which may develop into patterns of behavior because they meet short-term goals, even if the long-term impact of such patterns is negative. In this way, a given emotion regulatory strategy can be a double-edged sword (Thompson & Calkins, 1996). Psychopathology may most clearly be reflected in rigidity of emotion regulation, tending towards over- or underregulation, rather than being able to flexibly respond to environmental demands. For example, one hypothesized pathway to serious misconduct is a pattern of underregulation of anger combined with overregulation of emotions that are experienced as creating vulnerability but which may lead to increased empathy and inhibition of aggressive tendencies, such as sadness and anxiety (Cole, Hall, & Radzioch, 2009).

Most behavioral studies of emotion regulation focus on behavioral strategies that are relatively easy to observe, particularly ones that are response focused (i.e., occurring after the emotion has already occurred; Cole et al., 2004). This is an important difference with the neuroscience literature, which capitalizes on the sensitivity of neural measures to measure covert cognitive processes and thus focuses more on cognitive emotion regulation strategies like reappraisal. Cognitive emotion regulation strategies are often antecedent focused in the sense that they occur prior to an emotional experience being expressed (Gross, 1998b).

Also, behavioral research on emotion regulation has largely focused on early developmental periods (e.g., preschool), in part because, to observe emotion regulation, emotions much be induced and young children are potentially less likely to quickly regulate a response before observable signs are detectable. The neuroscience literature, because of the difficulties inherent in using neuroimaging technology with very young children, has tended to study children that are in middle childhood and older.

A recent measure development study (Gullone, Hughes, King, & Tonge, 2010), highlighting age-related difficulties in emotion regulation research, tested the utility of a version of the Emotion Regulation Questionnaire that can be completed by both children and adolescents (ERQ-CA), and is parallel to the version used in adults studies (Gross & John, 2003). The test was administered to 1,128 participants aged between 9 and 15 years, and given again one year later. Two key developmental findings emerged: Suppression was used more by younger compared to older children, and over time participants reported less use of suppression. Older participants also scored lower on reappraisal, but the use of reappraisal showed stability over time. This tool, however, does not provide a bridge between the adult and child literature for the age range in which much behavioral emotion regulation research is conducted (i.e., 3–7).

In summary, neuroscience can benefit greatly from considering the behavioral research on the development of emotion regulation: in particular, organizational models of development, consideration of changes in cognitive understanding, and deepened awareness of the short-term versus long-term costs and benefits of particular regulatory styles. Finally, future research that integrates behavioral and neuroscience approaches needs to bridge the gaps in terms of the age ranges, types of task, and target regulatory phenomena studied. Our findings should not be an artifact of the tools we use.

Social-Contextual Factors

Behavioral research has long been concerned with how a range of social and contextual factors influence child emotion regulation. Links between parenting and emotion regulation have been focused on in particular. Parents and caregivers provide direct intervention and support for children's nascent attempts to regulate emotions, through redirection, soothing distress, bolstering positive emotion, creating routines and schedules, encouraging infants' first attempts at self-expression, and offering assistance when children meet an emotional challenge (Fox & Calkins, 2003).

In addition to parenting strategies, the degree to which parents attempt to exert control over the child versus bolster and support child autonomous attempts to cope is a key factor in the development of emotion regulation (Calkins et al., 2002; Calkins, Smith, Gill, & Johnson, 1998). For example, Calkins and colleagues (1998) showed that mothers who used more negative and controlling parenting behaviors had children who showed greater use of non-adaptive strategies in emotional challenges. Another important factor to consider in the impact of parenting on emotion regulation is the notion of goodness-of-fit between caregiver and child. Goodness-of-fit refers to reflects the degree to which a parent sensitively responds to child emotion and behavior in terms of whether their own style and values "fits" with a child's behavior and temperament (Chess & Thomas, 1989; Dennis, 2006; Paterson & Sanson, 1999). Thus, different family environments and styles may be a better fit for some children than others, depending on the child's temperament. A key question for neuroscience research is whether neural patterns related to emotion regulation differ between children experiencing distinct types or qualities of parenting.

In addition, it is critical to take the context of emotion regulation into account (Buss, Davidson, Kalin, & Goldsmith, 2004; Coifman & Bonanno, 2010). Indeed, Cole et al. (2008) argue that a central indicator of difficulty with emotion regulation is the expression and experience of context-inappropriate emotion, such as anger and sadness in situations that children typically enjoy. Although there has been a push in recent years to identify biobehavioral profiles of disorder that include the context of development, relatively little integrative research has emerged that measures "brains in context." However, two themes have been highlighted—context sensitivity and flexibility.

Buss and colleagues (Buss, Davidson, Kalin, & Goldsmith, 2004) discuss the role of context sensitivity in relation to temperamental fearfulness as a risk factor in anxiety. They describe the notion of dysregulated fear as reflecting a combination of fearful reactivity and context appropriateness. That is, not all fearful children become anxious. Instead, potentially pathological fear mainly includes those fear responses that are insensitive to contextual demands and cues. They hypothesized and found that only fearful behaviors under low-threat contexts (freezing behavior during a free play with a stranger) was associated with biological indicators of increased stress reactivity—higher basal cortisol and sympathetic cardiac activity. More traditional measures of fearfulness, such as behavioral inhibition, did not predict physiological reactivity.

Bonanno and colleagues (Bonanno et al., 2007; Bonanno, Papa, Lalande, Westphal, & Coifman, 2004; Coifman & Bonanno, 2010) have discussed the role of context sensitivity in recovery from psychopathology, stress, and trauma. For example, in one study (Bonanno et al., 2007) individuals who suffered childhood sexual abuse were interviewed about their experiences of abuse as well as positive life events. Although displays of positive emotion overall were associated with better social adjustment two years later, those who displayed positive emotion while discussing their abuse showed poorer adjustment over time. This suggests that the participants' context-insensitive emotional responses may have reflected a more basic emotion regulatory problem that compromises positive adaptation. Similar findings from Rottenberg and colleagues (Rottenberg, Gross, & Gotlib, 2005; Rottenberg, Kasch, Gross, & Gotlib, 2002) suggest that individuals who currently meet the criteria for major depressive disorder versus those whose symptoms have remitted or are non-depressed show less ability to respond flexibly and appropriately to shifting emotional contexts—such as by being less emotionally responsive to both sad and amusing contexts (Rottenberg et al., 2002).

Another important notion is that that positive emotion regulation involves the ability to use strategies flexibly and to replace ineffective strategies with other potentially adaptive strategies (Bonanno et al., 2004; Thompson, 1994). In one study (Bonanno et al., 2004), New York City college students were examined in the aftermath of the September 11 terrorist attacks. Participants were asked to enhance or suppress emotional expressions in a laboratory task. Results supported the flexibility hypothesis such that participants who were better able to enhance *and* suppress emotional expressions evidenced less distress two years after the attacks.

Culture is another critical context that is thought to influence emotion regulation. Although relatively few studies directly examine emotion regulation and culture, there is a rich body of literature examining the cultural regulation of emotion (Mesquita & Albert, 2007). For example, recent findings suggest that how children are socialized to understand emotion shapes their evaluation of emotional events and their approach to regulating emotion. Cole and colleagues, examining beliefs about emotion in Nepalese children, found that as early as age 6, Nepalese children differ from American children in their beliefs about whether negative emotions should be expressed (Cole, Bruschi, & Tamang, 2002; Cole & Tamang, 1998).

In summary, while behavioral research has had a focused interest in social-contextual factors in emotion regulation, neuroscience is relatively naive to this viewpoint. Increased communication and collaboration among researchers may help mend this rift.

THE FOUR "W" FRAMEWORK

As can be seen in the review above, the behavioral and neuroscience literatures on child emotion regulation are not closely linked. While some similar themes emerge, we believe that the field of emotion regulation can greatly benefit from increased integration between behavioral and neuroscience approaches in order to improve cross-fertilization of theoretical perspectives and empirical findings. In the following, we describe the FourW Framework that highlights cross-cutting themes in emotion regulation research and which could serve as a framework for articulating how emotion regulation is being examined in a given study.

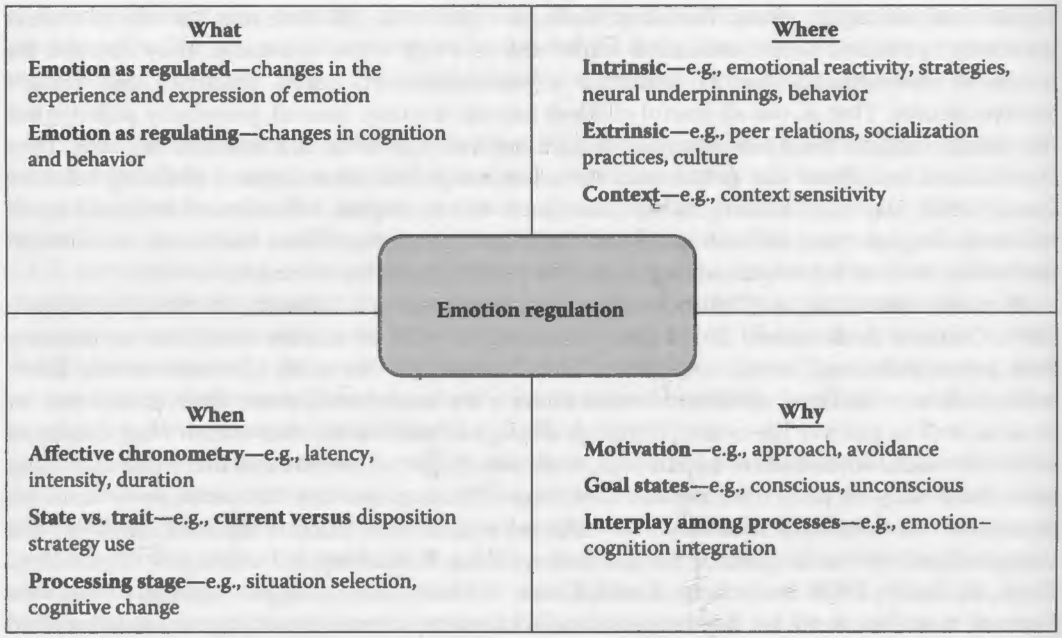

FIGURE 8.2 The FourW Framework.

While some have argued that adopting one specific definition of emotion regulation is optimal in order to advance the field (Bloch et al., 2010), we believe that this is unlikely given significant heterogeneity in viewpoints. Moreover, it may be unproductive if such an approach narrows the concept of emotion regulation too much. Another option is to develop a systematic way for researchers to communicate with each other about exactly how they are conceptualizing and measuring emotion regulation. This is what we have attempted to do with the FourW Framework—fostering both diversity in viewpoint and a common meeting ground (see Figure 8.2).

The FourW Framework includes four domains: What, Where, When, and Why. *What* refers to what is targeted as the "unit of analysis"—emotion as regulated or emotion as it regulates other processes. *Where* refers to where emotion regulation is being measured, whether these processes are intrinsic to the individual, extrinsic, and/or the context in which the process is measured. *When* refers to consideration of the timing of emotion regulation, whether the latency, rise, and fall of the emotional response or the nature of state compared to trait emotion regulatory tendencies. *Why* refers to a consideration of goal states that influence emotion regulation, as well as how multiple processes might interact to shape emotion regulation.

Not every study will necessarily include a consideration of each domain. We propose, however, that the FourW Framework could be used to systematically consider what aspects of emotion regulation are most relevant to a given study, to articulate what themes are being highlighted, and to consider alternative conceptual and measurement approaches.

For example, imagine a researcher who wants to ask the question: How do the neural processes underlying emotion regulation differ between anxious and non-anxious children? From the perspective of the FourW Framework, she would first identify *what* she is measuring. In this study, our intrepid researcher is using ERPs to examine similarities and differences in how anxious versus non-anxious children use reappraisal to modify emotional responses. Therefore, *what* would refer to emotion as being regulated. Next, she should focus on *where* she wants to measure the target process. She is interested in neural underpinnings of emotion regulation, and thus will emphasize intrinsic processes. In addition, this focus on the intrinsic is reflected in her targeting a specific emotion regulation strategy—reappraisal. Yet, our researcher is also interested in the context of measurement;

in particular, whether emotion regulation is occurring in a threat-relevant or irrelevant context and whether anxious children can show flexible use of reappraisal across contexts. Next, she takes time to consider *when* emotion regulation is happening. Here, she is limiting herself to considering one point in time, and so is concerned with state rather than trait. At the same time, given the excellent temporal resolution of ERPs, she will be able to characterize the affective chronometry of reappraisal with millisecond precision. Finally, she considers *why* emotion regulation is happening. Given her theoretical interests, she will examine how the interplay between anxious symptoms and attentional control has an impact on emotion regulation. Thus, the FourW Framework provides integrative consideration of cross-cutting themes in emotion regulation research, while facilitating the clear conceptualization of a given empirical question.

Future Directions: Balance versus Control

The question of *Why* in the FourW Framework, which includes the notion of the interplay among processes, highlights a key question that arises once the full complexity of emotion regulation is laid out in front of us: *How* do all these processes work together in support of emotion regulation? We believe a current Zeitgeist in neuroscience is highly relevant to this question: A focus on *balance* rather than control.

We have previously discussed the notion of balance in terms of "optimal balance" (Blair & Dennis, 2010; Dennis, 2010). While much emotion regulation research implicitly or explicitly states that emotion disorganizes and cognition organizes and controls, the notion of optimal balance considers how both emotional reactivity and control constrain and organize emotion regulation in support of positive adjustment. An optimal balance view also highlights that an appropriate or optimal balance between reactive and control processes differs across individuals and contexts, and that balance is not static—tracking the time course of emotion regulation will likely reveal time-sensitive changes in the nature and timing of balance and imbalance.

Here, we highlight four aspects of balance in regards to emotion regulation: integration, optimization, neural efficiency, and individual differences.

Figure 8.3 depicts this notion of balance and contrasts it with "control" models of emotion regulation. *Integration* refers to the idea that emotion is a *fundamentally integrated* process such that the affective properties of emotion cannot be isolated from cognitive, motivational, and behavioral domains (Campos et al., 1989; Frijda, 1986) and are instantiated in highly distributed neural networks (Rolls, 1999; Schore, 1999). What we call emotion regulation at the level of the brain is a cascading chain of processes capitalizing on the rich interconnectivity among neural regions involved in sensory processing, affective evaluation, homeostatic processes, basic physiological fight/flight responses, memory, higher order executive functions, and more. While we acknowledge that the control of emotion via high-order cognitive processes is a very important aspect of emotion regulation, we believe that to only describe emotion regulation in these terms is artificial, as are many reductionisms that serve the purpose of scientific parsimony.

In a basic sense, integration refers to a combination of parts that work together or form a whole in order to better achieve a common objective or set of objectives. Integration among discrete, yet interconnected systems underlying emotion regulation implies that distinct affective and cognitive processes work together to better achieve regulatory goals, and that specific states or functions can influence each other in selective ways (Gray, 2004; Gray & Burgess, 2004). For example, neuroimaging research by Gray and colleagues shows that experimentally induced approach- and withdrawal-related emotions selectively influence cognitive control functions, such as working memory (Braver, Cohen, & Barch, 2002; Gray, 2001, 2004): Amusement enhances verbal working memory whereas it compromises spatial working memory. Conversely, fear and anxiety enhance spatial working memory but compromise verbal working memory. These findings illustrate emotional facilitation and interference effects on cognition, and suggest that at some stage of task processing, emotion and cognition equally contribute to behavior (Gray, 2004). A range of emotions,

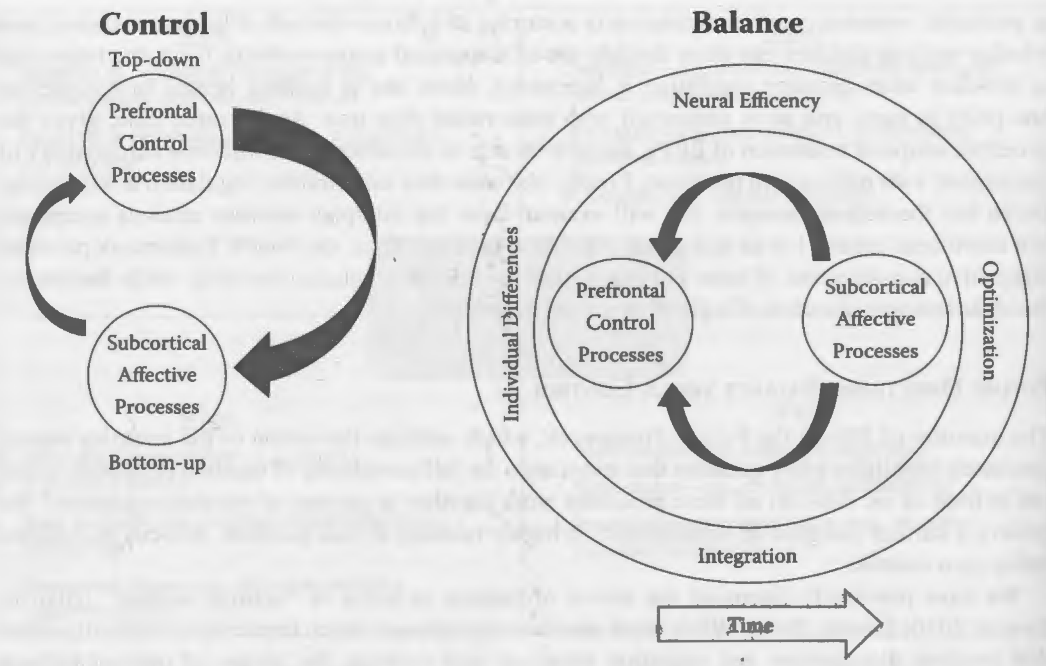

FIGURE 8.3 Control versus balance models of emotion regulation. Models of emotion regulation emphasizing top-down control (left panel) highlight the regulatory effects of prefrontally-mediated cognitive and behavioral control processes on subcortically-mediated affective and motivational processes. This cortico-limbic circuitry is also understood to underlie bottom-up regulatory effects of affect and motivation on control processes, but this influence is poorly specified and often thought to be weaker than that of top-down control. In contrast, models of emotion regulation emphasizing balance between top-down and bottom-up processes (right panel) highlight the mutual influence of these processes, while allowing that under some conditions, one or the other could exert the strongest regulatory effect. In addition, greater emphasis is placed on how the balance between control and affective processes dynamically change over time and developmental periods, and highlights principles of balance including neural efficiency, integration, optimization, and individual differences.

cognitive processes, and contexts must be assessed if we are to delineate the specific ways in which integration influences self-regulation.

Research on decision making and memory further highlights the importance of emotion–cognition integration. For example, when emotional functioning is compromised, social reasoning may be impaired. Damasio and colleagues' studies of patients with lesions to neural networks supporting emotional functioning show that social decision making is severely compromised in these patients (Damasio, Tranel, & Damasio, 1991). Other research shows that economic decision making is actually enhanced among more emotionally reactive individuals (Seo & Barrett, 2007), and that emotion bolsters both memory accuracy and a subjective sense of recollection (Phelps & Sharot, 2008). Indeed, recent neuroimaging research suggests that the OFC is a key neural area that serves to evaluate whether emotional information is contextually relevant for decision making (Beer, John, Scabini, & Knight, 2006).

Two other key concepts are *optimization* (Blair & Dennis, 2010; Dennis et al., 2010; Urry & Gross, 2010) and *neural efficiency* (Dennis, 2010; Gray, 2004; Luu & Tucker, 2004). Because the brain is capable of massively distributed information processing, these concepts describe how resources are balanced to accomplish goals. Models of emotion regulation in older adults (Urry & Gross, 2010) use the concept of *optimization* to explain how individuals commit time, effort, and resources to accomplishing emotion regulation goals. These resources may be internal or external

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SUMMARY AND KEY

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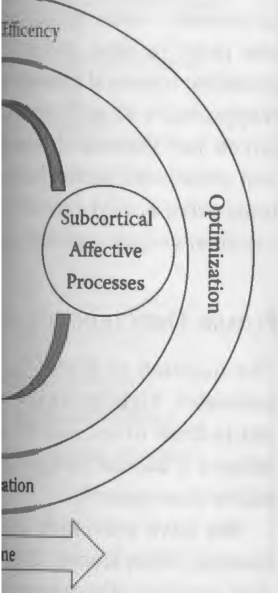

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(e.g., social support). Older adults may rely more on external resources to optimize their ability to accomplish emotion regulation, and compensate where necessary. *Neural efficiency* is a variant on optimization in the sense that it refers to the ability to use fewer and more focused neural resources to accomplish a goal. In our lab (Dennis & Chen, 2007) and others (Gray, 2004; Somerville & Casey, 2010), research on emotion–cognition integration uses the notion of neural efficiency to explain how emotion and cognition influence each other in the context of emotional challenges.

To understand the nature of integration, optimization, and neural efficiency, there is a critical need to take *individual differences* into account. That is, individual differences in state or trait emotionality (like anxiety or sensitivity to reward) are expected to modulate how emotion and cognition work together. For example, we (Dennis & Chen, 2007) examined whether attention to emotional information influenced attention performance differently among individuals varying in threat sensitivity. We examined an early frontal negativity, the N2, in response to distracting emotional faces as a measure of the attentional control resources individuals recruited to process the distracters. We found that N2 amplitudes to threat-relevant faces (fearful faces) was linked to sustained and even slightly improved executive attention performance among more threat-sensitive individuals, but with decrements in executive attention among low threat-sensitive individuals. Thus, the implications of recruiting cognitive resources under emotional demands may strongly vary across individuals: for some, higher levels of recruitment achieve balance and, for others, indicate imbalance.

Taken together, these concepts of integration, optimization, neural efficiency, and individual differences suggest that there is a need to expand out from "control" views of emotion regulation that mainly examine how "hot" emotions are regulated by "cool" top-down cognitive control processes to consider how positive and negative emotions can also organize behavior (Cole et al., 2004; Damasio et al., 1991; Izard, 2007; Luu & Tucker, 2004; Seo & Barrett, 2007). Moreover, it will be critical to examine how balance is achieved differently depending on developmental level, and how the nature of balance might dynamically change over time, from a timescale of milliseconds, to hours, days, and years.

This perspective is consistent with other models of self-regulation (e.g., Ernst & Fudge, 2009). For example, the affective evaluation hypothesis (Luu & Tucker, 2004) argues that reactive and control functions are mutually regulated in order to direct and control behavior. Focusing on conflict and error monitoring and other functions of the ACC, the model posits that that these processes intrinsically involve affective set points against which actions are monitored, and thus these cognitive control functions are constrained by emotional individual differences, contexts, and goals. Thus, affective processes are necessary for intact self-regulation. This view is rooted in cybernetic principles of homeostasis, set points, and feedback systems (Nauta, 1971; Pribram, 1960). Due to the massive interconnectivity between the prefrontal cortical and limbic networks, action plans represented in the cortex can be evaluated in terms of motivational and affective significance by limbic networks (Allman, Hakeem, Erwin, Nimchinsky, & Hof, 2001). Therefore, in a feed-forward fashion, emotional processing centers create expectancies and evaluative set points that are critical for ongoing feedback during action monitoring. A singular focus on cognitive control of affect is limited because it does not take into account the role of affective and motive set points in guiding plans and actions.

SUMMARY AND KEY RESEARCH QUESTIONS

In this chapter, we have proposed an organizing framework, the FourW Framework, and reviewed some of the key literature on emotion regulation. As a field, we are in the unique position to establish basic knowledge of neural processes underlying emotion regulation and its development, but to also pursue innovative questions that can expand notions of what emotion regulation is, how to target both linear and non-linear processes, and that carefully consider how adaptive (or maladaptive) emotion regulation may vary across individuals and contexts. We believe that some key research questions and directions for future research may be instrumental in moving us closer towards these goals:

1. *Can emotion regulation be conceptualized in terms of the balance between affective-motivational and cognitive control processes?* This would lead us to a range of new questions, such as whether dispositionally low levels of cognitive control benefit some individuals if they also show low levels of motivational and affective drives, or if they show enhanced affective drives linked to the inhibition of behavior, like fear and anxiety.
2. *How do we measure multiple aspects of emotional reactivity and control over time in order to understand how they work together to influence the development of emotion regulation?* Previous research suggests selective interactions between emotion and cognition (e.g., Gray, 2004). Thus, exactly what process we measure and how we measure it likely will have a profound influence on our findings.
3. *How can we better bridge the gap between behavioral and neuroscience research?* There is a need for more studies that combine behavioral and neuroscience methods in order to better identify brain–behavior correspondences that can facilitate application of neuroscience findings to prevention, intervention, and other real-world contexts.
4. *How can we better assess change and continuity in emotion regulation across development?* There is a pressing need to identify measures of emotion regulation that can be applied at multiple age periods in order to more effectively track developmental change and continuity. It is also important to consider how a given task may create very different demands and impacts across developmental periods—so developmental adjustments need to be made with great care.
5. *Can notions of dysregulated emotion in the behavioral literature be applied to neuroscience studies?* For example, Cole and colleagues (2008) highlight several key signs of dysregulated emotion: context-inappropriate emotion; emotion–behavior sequences in which an emotional experience is followed by an inappropriate or disruptive behavior; disruptions in the affective chronometry of emotion; the use of emotion regulation strategies that are immature or ineffective; and difficulty using social resources to recover from negative emotion.
6. *What are critical or sensitive periods in the development of emotion regulation?* Drawing from the behavioral science literature on stage-salient tasks (e.g., Cicchetti, Ganiban, & Barnett, 1991) may provide a useful framework for pursuing this question.
7. *What is "mature" emotion regulation from a neural perspective?* Does increased and more diffuse neural activity during emotion regulation reflect immaturity because it indicates neural inefficiency and greater effort? Or does it reflect more maturity because resources are being effectively recruited to perform emotion regulatory functions or tasks?
8. *What individual differences matter in emotion regulation?* Obvious ones to start with are gender and age, but there is a need to develop models that can provide theory-driven approaches to this question. Temperament theory (Derryberry & Rothbart, 1997) and neural models of self-regulation (Ernst & Fudge, 2009) among many other approaches (Higgins, 1997; Panksepp, 1998) suggest the importance of considering approach and avoidance motivational drives.
9. *How does regulation become internalized?* Developmental theorists have posited that children learn to self-regulate emotion and behavior via a gradual shift from primarily external (e.g., parenting) to internal sources of regulation (Kopp, 1982, 1989). How this internalization occurs is unclear and likely involves a range of social contexts and experiences, including attachment with caregiver (Cassidy, 1994), the success with which parenting successfully manages child arousal (Schore, 1999), and the impact of multiple social groups such as siblings (Garner, 1995; Volling, 2001) and peers (Cassidy, 1994; Deater-Deckard, 2001), all of which may differ across cultures (Dennis, Talih, Cole, Zahn-Waxler, & Mitzuta, 2007).

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These questions are ripe for research from a developmental neuroscience perspective. Neuroscience research on the development of emotion regulation is in its nascent stages, and is full of exciting challenges, conundrums, and promising early results. The wonderful diversity with which emotion regulation is conceptualized in the behavioral and neuroscience research adds great richness, but is also a potential weakness. We hope that this chapter will provide a conceptualization and directions for research to help move the field forward.

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