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The self-regulating brain: Cortical-subcortical feedback and the development of intelligent action

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Abstract

To speak of cognitive regulation versus emotion regulation may be misleading. However, some forms of regulation are carried out by executive processes, subject to voluntary control, while others are carried out by "automatic" processes that are far more primitive. Both sets of processes are in constant interaction, and that interaction gives rise to a stream of activity that is both cognitive and emotional. Studying the brain helps us understand these reciprocal regulatory influences in some detail. Cortical activities regulate subcortical activities through executive modulation of prepotent appraisals and emotional responses. Subcortical systems regulate the cortex by tuning its activities to the demands or opportunities provided by the environment. Cortical controls buy us time, as needed for planning and intelligent action. Subcortical controls provide energy, focus, and direction, as needed for relevant emotion-guided behaviour. We review the neural processes at work in both directions of regulatory activity, looking at the anterior cingulate cortex (ACC) as a hub of cortical systems mediating downward control, and discussing limbic, hypothalamic, and brainstem systems that mediate upward control. A macrosystem that displays both directions of control includes the ACC and the amygdala within a feedback circuit whose features vary with clinical-personality differences. Developmental changes in ACC-mediated self-regulation support advances in directed attention, response inhibition, and self-monitoring. Developmental changes in amygdala-mediated self-regulation involve the compilation of meanings that direct thought and behaviour, thus consolidating individual differences over the lifespan. In this way, the capacity to exert voluntary control develops alongside the accumulation of associations that trigger the responses that demand control. The balance between these developmental progressions has implications for personality formation and mental health.

Keywords: Self regulation; Emotion regulation; Brain development; Cognition-emotion interactions; Individual differences; Neural systems; Cognitive neuroscience; Feedback; Coordination; Corticolimbic interactions

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The purpose of this paper is to examine processes of self-regulation—how they work in real time and how they change over development—from a neural perspective. Its further purpose is to try to resolve the question of what's cognitive and what's emotional in self-regulation by showing how a neural analysis overcomes these distinctions. These objectives emerge from developmentalists' emphasis on self-regulation, their determination to resolve cognition/emotion ambiguities, and their broadly shared goal of anchoring psychological theory in neuroscience. We hope that, by the end of the paper, some real progress toward these ends will be made. But if we start off trying to define our terms, as is often done in theoretical articles, we find ourselves in a quandary. The problem begins with both halves of the phrase "self-regulation" and then gets worse when we try to distinguish cognitive and emotional functions. And though it's not a problem that is deeply troubling for psychologists, it becomes particularly nettlesome for neuroscientists. We begin our analysis with a look at these definitional conundrums in the remainder of this section. Then, in the following section, we offer some suggestions for resolving them. The remainder of the paper builds on these suggestions.

Regulation usually refers to controlling and making right some process that would otherwise run away or vary in undesirable ways. We want to regulate the pressure in a boiler or an engine, the temperature in the barbecue, or the propaganda being broadcast by some unsavory organization. A classic example of regulation is thus a thermostat. The furnace is not something you want to stay on, nor to turn on and off haphazardly. It's something you want to control, regulate, make regular. This is accomplished by a negative feedback loop between the controller—the thing on the wall—and the controllee—the furnace itself. When it gets too hot, the furnace is turned off. When it gets too cold, it's turned on. That's regulation in a standard mechanical system.

But the brain is not a standard, mechanical system. It's a highly complex network of components that interact reciprocally, multiply, and recursively. Moreover, it's a biological system, and that usually means that the interaction of the components changes their structure. The brain is also fundamentally a self-organizing system. It shifts from states of lower organization to states of higher organization by itself. This happens both in real time (e.g., 500 ms) and in development (e.g., from infancy to school age). Across both time scales the brain shifts from states of relative disorder to states of massive coherence. In real time, neural self-organization occurs whenever one pursues a goal, reacts to an environmental challenge, swats a fly, recalls a poem, or strikes a tennis ball. Its mechanism is synaptic and neurochemical synchronization. In development, neural self-organization is demonstrated by the acquisition of cognitive structure, as reflected in the capacity for adults to concentrate on a chess problem for hours whereas preschoolers can barely sit still for five minutes. Its mechanism is synaptic pruning and myelination throughout the cortex and limbic system. Like other self-organizing systems, the brain functions through multiple, nested feedback operations: not only negative feedback, by which activities stabilize one another, but also positive feedback, by which activities augment or promote each other. We have reviewed these principles elsewhere (Lewis, 2005a, 2005b; Lewis & Todd, 2005). For our present purposes, the point is that there's nothing like an activator (the furnace) coupled with a controller (the thermostat) anywhere in the nervous system. So it's hard to see any particular neural process in terms of regulation.

The term "self" is problematic as well. There is no self in self-organization (Lewis & Granic, 1999). Self-organization means auto-organization, without the necessity of some central agency like a self. However, we developmentalists often talk about "the self" in the folk-psychological way: a sense of identity, continuity, and a center of our subjective experience. Even if we take a self to be involved in the neural activities that make up psychological experience, and even if we can figure out what we mean by regulation, the question remains: does self-regulation refer to regulation by the self or of the self? Or does it mean regulation by the self of the self? The problem doesn't end there, because most theorists who study the self acknowledge many levels of self. There can be a subjective versus objective self, and there can be a primitive, affective self—a self that experiences basic emotions, for example—as well as a self that is supervisory or deliberate. Different brain regions have been associated with these levels or types of self (e.g., Damasio, 1999; Panksepp, 1998), so it might be possible to think of a higher-order, supervisory self-regulating a more primitive, subjective self and to map out these relations with neural precision and realism. On the other hand, it might be possible for a more primitive self to regulate the reflective cognitive operations usually associated with the higher-order self! This problem remains nearly intractable until we can properly define the term "regulation" as it applies to neural events.

The intent of this special issue is to try to integrate our notions of cognitive and emotional regulation, or at least to look at the relations between cognitive and emotional processes in our understanding of self-regulation. Psychologists have long sought to resolve the fundamental disjunction between cognitive and emotional functions. But what is notable and perhaps alarming is that research on self-regulation has perpetuated this disjunction rather than resolve it, for example by drawing a line between "cool executive function (EF)" involved in purely cognitive activities and "hot EF" involved in emotion regulation (Zelazo & Cunningham, 2007; Zelazo & Mueller, 2002). Nevertheless, the attempt to reconcile cognitive and emotional processes gets turned on its head when we examine the brain. This is because, in every part of the brain, from the cerebral cortex to the brain stem, it is usually impossible to assign either cognitive or emotional functions to any particular structure. Many structures do both. For example, the amygdala can be said to be involved in appraisal, a cognitive process, as much as in fear and rage reactions or subjective emotional feelings. And the nuclei in the brain stem that mediate stereotypic responses such as freezing in the presence of fear are tightly coupled with neighboring nuclei that perceive (i.e., *appraise*) a rapid movement, whether a snake in the grass or a face on a dark street. Moreover, even where some structures lend themselves to be more easily designated as cognitive (e.g., the dorsal PFC or hippocampus) or emotional (e.g., the septum or hypothalamus), these structures become functionally coupled within milliseconds whenever the brain self-organizes, that is, whenever the brain is called into action. Even the brain stem nuclei that we just mentioned *could* be separated into a response emitter and an environment reader, which *could* be designated as more emotional versus more cognitive. But they always work together, so why bother? Lewis (2005a) reviewed these issues and concluded that all brain processes have cognitive appraisal aspects (i.e., interpretation of the world) and emotional response aspects (i.e., an urge to act in keeping with that interpretation). But the main point for now is that the categories "cognition" and "emotion" fall apart when looking inside the brain. The tightly packed, intricately interrelated cortices and nuclei of the brain work together to generate psychological states and action patterns that are both cognitive and emotional. It's left to psychologists to do the parsing.

1. Vertical structure in the brain

Let's try to resolve the second problem first. If we can't divide neural structures and activities into cognitive versus emotional, can we at least find a brain dimension that roughly corresponds to our intuitive or folk-psychological distinctions between emotional responses and cognitive interpretations? Luckily, we can: the vertical dimension. This is not so much a straight line from the neck to the top of the head, but an imaginary axis that moves up and out from the most primitive regions, at the medial core of the brain, to the most advanced and evolved structures, sitting either above (more dorsally) or outside (more laterally) these regions, as epitomized by the cerebral cortex. This dimension is often called the neuroaxis, and it passes through four major levels:

the brain stem, the diencephalon (thalamus and hypothalamus), the standard limbic structures (e.g., hippocampus, amygdala) and basal ganglia, and finally the cerebral cortex itself (see Lewis, 2005b). The vertical dimension can do a better job than the cognition-emotion delineation because, even though no distinct parsing is implied, activities deemed "cognitive" in folk-psychological terms are often more conscious and deliberate, and therefore mediated by structures higher up the neuroaxis, whereas those deemed "emotional" are often impulsive and automatic, and therefore mediated by lower levels of the neuroaxis, from the limbic system on down. Deliberate control requires corticolimbic mediation, whereas states of action readiness (see Frijda, 1986, 1993) require mediation by the hypothalamus and brain stem. Interestingly, the term "self" can also be polarized to mean a higher self and a lower self along the same dimension, and we'll return to this idea later.

Without going into too much detail, we can characterize the lower levels of the neuroaxis (e.g., brain stem, midbrain, hypothalamus) as (1) phylogenetically earlier and therefore in some sense more primitive, (2) more directly wired to bodily systems, as epitomized by the cranial and spinal nerves that enter and leave the brain stem and the regulation of the autonomic nervous system by the hypothalamus, (3) highly structured at birth and generally lacking in plasticity, thus not structured through learning, (4) critically involved in manufacturing and releasing neurochemicals that adjust higher-brain (as well as bodily) processes to correspond to motivational states, and (5) critically involved in releasing motivationally relevant behavioural responses such as rage and fear reactions (e.g., from the hypothalamus and periaqueductal gray [PAG] region of the brain stem). These "lower" brain systems are not associated with conscious cognitive processes but with more automatic perceptual and behavioural functions. Higher-brain systems rely on these structures to function properly, but the reverse is not true. Decorticate animals can behave appropriately in most situations, relying only on their lower brain structures.

The higher levels of the neuroaxis can be characterized as (1) phylogenetically later and therefore supporting more sophisticated functions, (2) directly connected to other (lower) brain systems but not to bodily systems or sense organs (except the sense of smell), (3) relatively unstructured at birth and highly plastic, thus designed to be shaped and reshaped by the animal's history of learning, and (4) implicated in deliberate, executive activities associated with conscious or effortful self-control. The cortex, and particularly the prefrontal cortex (PFC) epitomizes these features. The cortex is the brain structure through which most learning takes place. It is also the structure that permits voluntary or executive control in typical cognitive tasks. Most important, it exercises this control by interposing such processes as context-updating, comparing, planning, and decision-making between a perceived stimulus and a behavioural response.

The PFC is almost completely made up of association cortex, and thus does not process raw sensory or motor information. Rather, it processes information about the world and about our own motor actions that has already been "cooked" (i.e., abstracted and condensed) by other cortical regions. Mesulam (2002) describes the prefrontal cortex as the apex of the neural hierarchy. The PFC is what saves us from the "default mode" of stimulus–response, in contrast to our reptilian ancestors. We might revise Mesulam's argument (and adapt it more specifically to mammals) by saying that the push from stimulus to *emotion* to response is what gets interrupted by the involvement of the prefrontal cortex. Indeed, this override of emotional impulses via processes of interpretation, set-switching, and planning permits the intelligent action of which we humans are so proud. Building on a concept introduced by Saarnat and Netsky (1974), Tucker, Derryberry, and Luu (2000) suggest that each higher level of the neuroaxis, culminating with the prefrontal cortex, contributes to intelligent action by stretching out the time between stimulus and response. If all we had was a brain stem, the perception of motion would immediately lead to freezing behaviour.

If we were stuck at the level of the limbic system, we would use stored meanings to automatically assign preference and value to certain stimuli and certain outcomes: our actions would be slowed down enough for "meaning" to intervene. Luckily, with the possession of a prefrontal cortex, we can slow down action almost indefinitely, allowing higher cognitive processes to compare and discard many possible plans or strategies in favour of what is likely to be most beneficial in the long run. Tucker's notion of slowing down the progression from stimulus to response captures the essence of executive processes. To be deliberate is to be reflective rather than impulsive.

We have seen that the structure of the brain lends itself to distinguish more deliberate functions, mediated by learning in phylogenetically advanced structures, from more automatic functions that are essentially built in at birth, mediated by phylogenetically earlier structures. This polarity works much better than any attempt to delineate cognitive and emotional functions in neural tissue. But does this reinterpretation help us with difficulties inherent in the phrase "self-regulation"? Yes and no. In one sense, the phrase *self-regulation*, or any notion of regulation, remains awkward when discussing the brain. As noted before, there is nothing like a regulator and a regulatee in the brain. There is no single action that requires regulation by a particular control system. In fact, however, when we take this problem seriously, the meaning of regulation mushrooms into something much more interesting than the workings of a thermostat. The entire brain is designed to regulate bodily processes, including neural activities which are themselves bodily processes. Thus, the entire brain is both a regulator and a regulatee; it is both regulating and self-regulating. Let's explore this idea globally at first, and then pursue specific kinds of regulation that might complement each other in a self-regulating brain that changes with development.

2. Self-regulation revisited

Theories of autopoiesis (Maturana & Varela, 1987; Varela, Thompson, & Rosch, 1991) characterize the self-organization of the nervous system as an evolutionary process that gives rise to embodied cognition. They explain that simple, one-celled animals did not require a nervous system because sensory input and motor output were processed by the components of a single cell. These components did not have to communicate with each other because chemical changes at the sensory surface directly produced chemical changes at the motor surface of the cell. When multicellular animals evolved, a problem arose. Sensory functions were specialized within certain cells, often at one end of the organism, whereas motor functions were specialized within other cells, often at the other end. Your eyeball and your big toe are not directly in touch! For action to be sensitive to perception, and therefore useful and adaptive, a new kind of cell had to evolve: one with long stringy extensions that could travel from one group of cells to another (Maturana & Varela, 1987). These cells are nerve cells or neurons. Their job was to regulate action in a very obvious way: to bring the firing patterns of muscle cells into line with the opportunities and threats afforded by the environment. As nervous systems evolved, and nerve cells began to cluster together in ganglia and then primitive brains, their function remained essentially the same. With higher animals, it is clear that all muscular actions, from the waves of motion in the esophagus, to the movements of the legs and hands, to the movements that tune sensory organs such as the eye, have to be aligned with what's going on in the world, including the outcomes of the animal's own behaviour. They require perceptual information to do that. Thus, the function of the brain is to regulate all bodily processes so that they are attuned to the ever-changing stream of events in the world.

Because the brain itself is a bodily process, it also must be tuned to the realities of the world. In real time, the brain has to know what's important, and emotion plays a key role in highlighting exactly that. In development, learning tunes the brain to the details of a specific environment, and learning is always guided by emotion as well (Izard, 1993). Thus, the brain is the fundamental organ of self-regulation, whether we mean regulation of the action systems of the body or, more broadly, of all bodily systems, including the brain itself. As a final word, all self-organizing systems must be self-regulating. They must remain controlled. Self-organization, when unfettered, leads to breakaway novelty, which leads inevitably to death. Cancer is an obvious example. So it is not surprising that the part of the body that is truly self-organizing is also the part most strongly implicated in self-regulation.

To call the brain the seat of self-regulation is not just a philosophical exercise. There is great utility in recognizing that all parts, systems, actions, and interactions within the brain are fundamentally involved in regulating either other parts of the nervous system—the brain itself—or else other bodily systems. Moreover, in keeping with Cole, Martin, and Dennis (2004), we can say that the psychological functions that emerge from the brain—the cognitive, emotional, and action functions—are both regulating and regulated. Yet we don't need to worry whether it's emotion that regulates cognition or vice versa in any particular neural process, given the impossibility of ever parsing these functions neurally in the first place. Not only must the brain regulate the body and be regulated itself in keeping with external realities, but it must also regulate and be regulated in keeping with internal realities. The role of the hypothalamus exemplifies this regulation. Moreover, bodily states change with needs, drives, and external conditions. Whether the animal needs to get warm, get supper, or get sex, bodily changes must be coherent and adaptive, and the brain's capacity to register and regulate different motivational states (including drives and emotions) makes this possible. Thus, changes both inside and outside of the body require bodily adjustments that constitute regulation, and the brain is the source of much of that regulation (although there are also self-regulatory loops outside the brain, for example in the structure of the muscles and organs themselves).

But how exactly does the brain *do* regulation? Instead of thinking of regulation in terms of damping or increasing the activity in one system by means of another, the notion that best applies to regulation within a complex system such as the brain is *coordination* among a number of different component systems. Brain parts become regulated (and regulating) by becoming coordinated with each other. In a way, this is an empty assertion. Brain systems can only be instrumental in doing *anything* through coordination. No brain system can accomplish anything on its own. For this reason a great deal of research has been devoted to mapping out the functional integration or synchronization of different brain regions. Functional magnetic resonance imaging (fMRI) is one of the primary methods that have aided this pursuit. Areas that "light up" at the same time, or whose degree of activation is correlated, are presumably working together, that is, they are coordinated, in the service of some function or activity. At a different level of analysis, phase synchrony between different brain regions is measured by the correlation of activity within the same frequency range, or the actual cross-correlation of the waveforms themselves, as measured by EEG techniques. Not surprisingly, coordination is also the mechanism by which cognitive systems self-organize, as modeled by neural networks and epitomized by human cognitive development. The role of coordination in developmental self-organization has been emphasized by pioneers such as Thelen and Smith (e.g., 1994, 1998).

Do we get any extra mileage by saying that coordination underpins regulation per se? Yes. Coordination is a fundamental mechanism of stabilization. In self-organizing systems, the ongoing co-activation of multiple components exerts a damping influence—not just on a single target subsystem—but on the overall system itself. This provides a sort of antidote to the positive-feedback properties that propel spontaneous growth. Coordination as self-stabilization offers a neat generic model for self-regulation in complex systems such as brains or neural networks (Lewis, 2005a). But we get even more mileage from examining coordination if we get specific about *what* systems become coordinated given a particular regulatory activity. And here we find ourselves in a much better position having discarded the psychological categories of cognition versus emotion and replaced them with levels along the neuroaxis from more automatic to more deliberate. Coordination across levels of the neuroaxis is a powerful vehicle for self-regulation, and specifying particular structures at particular levels opens the door to a precise descriptive language for modeling psychological self-regulation using neural terms. This idea is explored in detail in the following section.

Before moving on, however, there are two additional points to highlight. First, our focus on coordination provides a segue to one of the most central themes in developmental thinking: the idea that development is comprised of differentiation and coordination. Coordination is the process that consolidates and thereby "regulates" whatever new structures are created through processes of differentiation, yielding progressively more powerful schemas or skills. For both Piaget and for neo-Piagetian theorists, higher levels of coordination explain progressive stages of cognitive development (e.g., Case et al., 1996; Mascolo & Fischer, 1998). A classic example from Case's theory is the acquisition of the concept of a number-line by dint of coordinating simpler schemas for numerosity and quantity. This coordination is the hallmark of developmental advancement into the first substage of dimensional thinking at about the age of 6 years. This coordinative structure literally regulates mathematical thinking, so that children do not have to rely on more haphazard strategies such as finger-counting when adding two numbers together (Case et al., 1996). The role of coordination in emotional development is even more clear, as epitomized by the concept of emotion regulation. The classic capacity to explicitly and effortfully inhibit emotional impulses, appearing at about age 3–4 years, seems to involve the coordination of one's own wishes with those of others (Eisenberg et al., 1996) or representations of immediate gain with those of long-term losses (Prencipe & Zelazo, 2005; Thompson, Barresi, & Moore, 1997). Thus, the theme of coordination *as* regulation helps integrate some fairly heterogeneous notions of what changes with development in a language that most developmentalists find convenient. As children develop, as coordination becomes more powerful and sophisticated, children become better regulated—in all kinds of ways. Their thinking, speech, emotional functioning, physical prowess all become better regulated . . . or, simply, better. We return to this theme later.

One final idea to help synchronize notions of coordination and regulation is the concept of intentionality as discussed by Walter Freeman. Freeman (e.g., 1995, 1999, 2000), one of the most advanced holistic theorists in neuroscience, describes intentionality as the superordinate function of all brain activity. By intending, or "stretching forth" intentionality, the animal's goals synchronize the activities of disparate brain regions in a self-organizing unity centered in the hippocampus and surrounding cortical tissue. Freeman uses *intentionality* to mean attention and action directed toward an expected outcome or goal. What preoccupies the brain is not what is happening in the world right now but what is about to happen as the current course of action unfolds and the animal's goal is pursued or altered. Intentionality is thus the thrust toward fulfillment of a goal in space and time. Because the hippocampus supports a model of the self in space and time, it is plausible to specify the hippocampus as the epicenter of neural self-organization. However, in our own modeling, we speculate that other neural systems, such as the hypothalamus or amygdala, could also be considered as epicenters of self-organizing neural activity involved in self-regulation.

For Freeman, intentionality creates coordination among brain structures in the service of directed action. And in this sense, intentionality regulates everything the animal does—both in perception and in behaviour—aligning it to an anticipated outcome toward which all neural and bodily processes are tuned. We utilize this idea in construing higher levels of self-regulation—those involving deliberate, intentional activity—as more comprehensive and more conscious. But we do not see them as always being dominant. We can easily imagine less comprehensive agendas dominating self-regulation, as epitomized by the power of emotional states to organize and direct thought and behaviour. Freeman also talks about the role of emotion in guiding intentionality through the subjective experience of need, want, fear, passion, and so forth. However, Freeman sees intentionality as a unitary state, centered in the most advanced levels of the brain: the cortex and hippocampus. We replace this view with an emphasis on different loci and levels of self-regulation, mediated by different structures distributed along the neuroaxis. We then speculate on the functions of these distributed loci and levels and we examine how they become harmonized to greater or lesser degrees over development. In summary, we replace Freeman's idea of a single epicenter of intentionality with a picture of multiple neural systems, interacting and competing, each with its own function and regulatory role. We propose that these systems become coordinated in different configurations when the brain settles into different modes of self-regulation.

3. Cortical versus subcortical mediators of self-regulation

Most interactions among brain parts (e.g., cells, regions, structures, systems) are reciprocal at a global level of analysis, such that activation flowing from one structure to another is reciprocated by activation flowing back from the second structure to the first. There are many examples. Perceptual information flowing from sensory to prefrontal cortices is reciprocated by information tuning the sensory cortices to the objects of attention. The cortex initiates an amygdala response based on perceptual information or expected outcomes, while the amygdala harnesses cortical activity according to the emotional meaning of the stimulus. Nevertheless, at a finer level of analysis, nerve pathways are unidirectional, and looking at the origins and targets of neural connections provides a detailed picture of how patterns of coordination originate and stabilize. Pathways descending along the neuroaxis have led theorists, beginning with Hughlings Jackson, to emphasize the inhibition or subordination of lower structures (e.g., the hypothalamus) by higher structures such as the cortex. However, it is also well known that these higher structures could not function without being energized or fueled by lower structures, such as nuclei in the brain stem that release neuromodulators along ascending pathways. In fact, a great variety of axonal pathways travel up and down the neuroaxis, supporting informational traffic that is, ultimately, reciprocal and bidirectional. A number of theorists see this information flow as the basis of *vertical integration*—the synchronization or coordination of activities all along the neuroaxis through reciprocal directions of influence (see Fig. 1).

Vertical integration appears to be responsible for the rapid synchronization of the entire brain (Tucker et al., 2000) whenever a significant change in internal or external events triggers the initiation of a cognitive, emotional, and/or motor response. Vertical integration synchronizes all levels of the neuroaxis, from the most sophisticated cortical functions to brainstem mediation of stereotypic action tendencies. It is therefore needed to coordinate perception, attention, and action planning with basic motor routines, so that the animal can behave flexibly, skillfully, and intelligently when motivated (Tucker et al., 2000; cf. Buck, 1999). In recent work, Lewis (2005a) identified several mechanisms through which vertical integration comes about. Most important among these are reciprocal (feedback) circuits among participating structures and neuromodulatory actions that enhance particular global organizations. Both processes may depend largely on the temporal phase-locking of activity between neural populations up and down the neuroaxis.

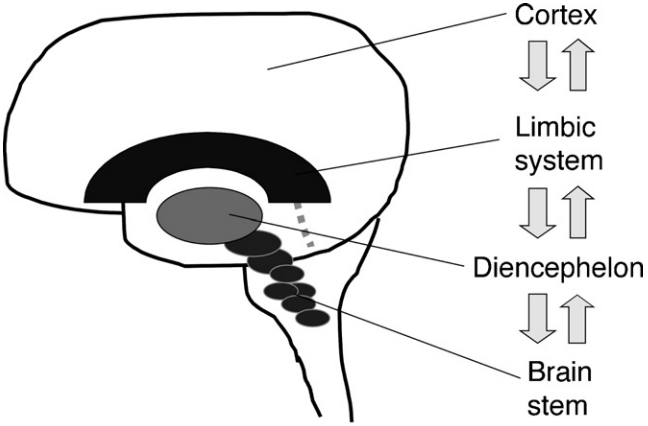

Fig. 1. Vertical integration in the brain. Vertical integration involves the synchronization of neural processes up and down the neuroaxis, from brain stem to cortex. The downward flow of information illustrates regulation by deliberate, executive processes controlling emotional response systems, whereas the upward flow illustrates the regulation of cortical processes by subcortical structures subserving motivated attention and perception.

Thus, vertical integration can be described as a holistic process of consolidation that occurs rapidly in real time. This is a handy description because it emphasizes the spontaneous coordination of disparate brain systems into a unified pattern of activity dedicated to a particular function: for example the formation of a goal, the flash of an emotional reaction, or the initiation of an action. But in the present paper we want to emphasize the roles of several *component* systems whose inputs and outputs give rise to specific coordinative patterns within the larger composite of vertical integration. These component systems have very different characteristics when it comes to self-regulation, and these differences become most apparent when we make comparisons across episodes, individuals, or developmental levels. One could say that the epicenter of self-regulation resides in one system, or in the circuitry connecting several systems, for a particular individual on a particular occasion. That epicenter may shift to another system or set of connections when the situation changes, under the influence of some drug, or—most important for our analysis—with development (see Johnson, 1999, 2000, for a developmental model based on intersystemic coordination). Thus, for example, a highly active amygdala (resonating with a finely tuned visual cortex) may commandeer neural coordination when one is tramping through a snake-infested swamp, making this region the epicenter of self-regulation. But an hour later, prefrontal cortical systems will recruit new patterns of coordination, and thus serve as a new epicenter of self-regulation, when one is selecting a campsite and erecting a tent—at least until someone brings out the beer.

3.1. Cortical self-regulation

One of the systems most often highlighted in the discussion of self-regulation is the anterior cingulate cortex (ACC). We restrict our discussion of cortical self-regulation to the ACC to provide a relatively detailed model, but other cortical systems could be highlighted just as easily. The ACC is arranged along the medial surfaces of the prefrontal cortex, where it curves around the corpus callosum (Fig. 2). Sometimes it is divided into a more “cognitive” component, along its dorsal (top) extent, and a more “emotional” component, along its ventral (bottom) or rostral extent (e.g.,

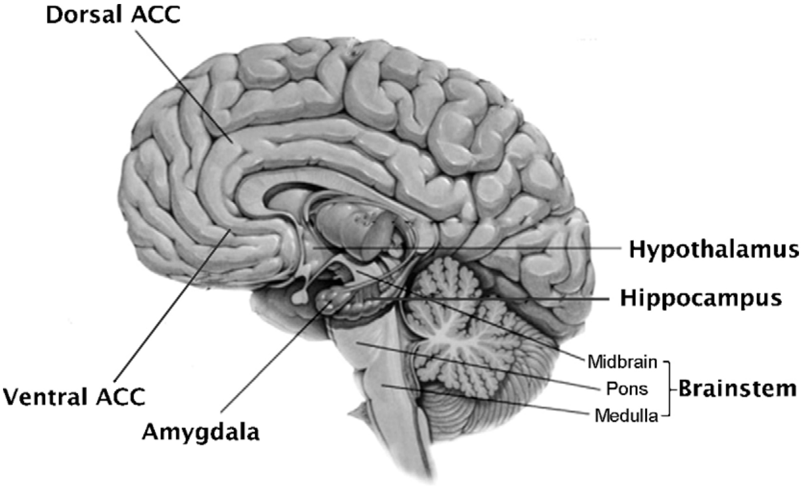

Fig. 2. Brain regions implicated in cortical and subcortical regulation processes. Dorsal and ventral zones of the anterior cingulate cortex (ACC) may function as epicenters of cortical self-regulation. The amygdala, hypothalamus, and brain stem may serve as subcortical epicenters of self-regulation.

Bush, Luu, & Posner, 2000). The ACC is one of the cortical systems which is most interior, most distant from the surface of the head, and thus most adjacent to subcortical limbic structures at the core of each hemisphere. As a result, some theorists see the ACC as occupying a middle ground between the neocortex and limbic system, and refer to it as limbic or paralimbic cortex. Tucker (e.g., 2001) views the cingulate as an extension of the dorsal trend of the limbic system, and thus a cortical outgrowth of the hippocampus (HPC). However, the ACC is also connected with the amygdala (AM), hypothalamus (HTh), and brain stem, such that it can directly influence structures that mediate associative memories, emotional responses, primitive behavioural routines, and the physiological states necessary to support them (Critchley et al., 2003; Petrovic, Kalso, Petersson, & Martin, 2002; Pezawas et al., 2005; Poremba & Gabriel, 1997; Price, 1999).

Although it is connected with subcortical structures, the ACC can also be viewed as a more phylogenetically advanced structure that plays a unique role in higher cognitive processes (Allman, Hakeem, Erwin, Nimchinsky, & Hof, 2001). The dorsal ACC is closely connected to the dorsolateral PFC (DLPFC), which is responsible for the temporary activation of information in working memory necessary for decision-making, planning, and problem solving (Paus, 2001). It may therefore play a mediating role between the HPC and DLPFC, initiating the retrieval of episodic information and maintaining its activation in working memory (Mesulam, 2002; Petrides & Pandya, 2002). The ACC is also closely connected to the supplementary motor area, where new actions are formulated (Goldberg, 1985). Thus, the ACC is involved in generating or selecting previously learned actions in the service of decisions made according to information in working memory.

Based on its anatomical connections, what aspects of self-regulation are mediated by the ACC? The ACC is implicated in the control or regulation of executive attentional processes (Frith, Friston, Liddle, & Frackowiak, 1991; Gemba, Sasaki, & Brooks, 1986) as well as emotional responses and emotional consciousness (Barbas, 1995; Lane et al., 1998). It is activated in order to assert control of behaviour in challenging situations, select among alternative response options, shift attentional sets, monitor errors, and alter behavioural strategies (Luu & Tucker, 2002; Posner

& Rothbart, 2000; van Veen & Carter, 2002). Perhaps most notably, it is activated when one must assert one's will in uncertain or conflictual circumstances (Paus, 2001). As observed by Amodio and Frith (2006), the kind of self-regulation mediated by the ACC concerns anticipated actions, and its role is often construed in terms of action-monitoring (e.g., Luu & Tucker, 2002). Thus, the ACC is implicated in many regulatory functions associated with conscious and effortful control. It epitomizes a style and level of self-regulation that is deeply interpenetrated by conscious decision-making and deliberate self-guidance, and this distinguishes it from the forms of self-regulation mediated by subcortical structures. In fact, even the orbitofrontal cortex (OFC), another paralimbic cortical system that is often associated with higher-order self-regulation, may be more responsive to anticipated information from the environment (Amodio & Frith, 2006) than to conscious intentions.

As noted earlier, coordination is the mechanism by which brain systems exert their regulatory function. Indeed, the ACC regulates attention, action, and emotional responding through its connections to other brain systems, including the DLPFC, OFC, medial anterior PFC, HPC, AM, HTh, and brain stem. These connections permit the coordination of ACC activation with activation of other structures. It might be possible to characterize each of these sets of connections as underpinning processes that are more cognitive or more emotional. But, as argued earlier, this would result in an imprecise and probably indefensible parsing of brain systems into psychological categories. What seems more beneficial is to group these connections according to their position along the neuroaxis, and to characterize the type of regulation they mediate. Thus, connections with prefrontal cortical areas (e.g., DLPFC) regulate executive processes that involve planning, judgment, decision-making, self-monitoring, and conscious control. Connections with limbic structures regulate memory activation and the selection of responses on the basis of episodic memory (HPC) and associative memory (AM). Connections to the HTh regulate physiological processes and bodily states. And connections to the brain stem regulate stereotypic motor responses as well as neurophysiological arousal. These regulatory processes can involve inhibition, alteration, recruitment, or enhancement, depending on the big picture of multiple coordinations converging across the entire brain. Nevertheless, the role of the ACC in these regulatory activities is quite easy to characterize. The ACC is a prefrontal cortical structure, and ACC activity allows for deliberate or conscious control. Coordinations with the ACC connect many other brain regions to a neural system that is responsible for directed action and voluntary choice. Moreover, if self-regulation means regulation not only *of* a self but also *by* a self, then the kind of "self" that characterizes ACC-mediated regulation is a higher-order, executive self; a deliberate, goal-oriented self; the kind of self we are mostly likely to identify with as intelligent and forward-looking.

3.2. Subcortical self-regulation

Now let's shift the focus to structures located further down the neuroaxis: the amygdala, hypothalamus, and brain stem. In discussions of self-regulation, these structures are generally viewed as the *objects* of regulation (e.g., Davidson, Putnam, & Larson, 2000; Ochsner et al., 2004). But can we view these structures as regulating entities in their own right? Neuroscientific research looking at bottom–up processes of "motivated attention" suggest that we can. For example, fMRI evidence indicates that activation in regions of the visual cortex increases with the intensity of emotional stimuli, and that feedback from the amygdala enhances perceptual responses to threatening stimuli (e.g., Surguladze et al., 2003). Moreover, electrophysiological studies have found that emotionally salient and arousing stimuli elicit more coordinated activity in frontotemporal and frontoparietal networks than neutral stimuli (Keil et al., 2003; Moratti, Keil, & Stolarova, 2004). These results are consistent with the hypothesis that cortical attentional networks, which guide perceptual processing, are tuned by activity in the amygdala and other subcortical structures. Yet even if they regulate cortical processes, can subcortical structures be said to serve as hubs of coordinated neural activity? And if so what sort of regulatory properties might these hubs exhibit?

The most obvious example of regulation by subcortical structures is that provided by the flow of neuromodulators. Neuromodulators are a specific class of neurotransmitters whose effects are indirect and global. Neuromodulators ascending from the brain stem to the cortex change the receptivity of cortical neurons to other neurotransmitters or else they change the quantity or impact of those neurotransmitters once they are released. The classic neuromodulators are dopamine, norepinephrine, acetylcholine, and serotonin. Some theorists also include the neuropeptides (e.g., opioids, oxytocin, etc.) among them. These chemicals are all released from one of three adjacent systems: the brain stem (especially nuclei within the pons and midbrain), the basal forebrain (a group of nuclei that specifically fuel the cortex), and the hypothalamus. The neuromodulators help activate brain processes mediated by the cortex and limbic system, as suggested by the phrase "reticular *activating* system". However, their action is actually far more complex. As reviewed elsewhere (Lewis, 2005a), each neuromodulator enhances activation in some parts of the brain while inhibiting activation in others. Thus, each neuromodulator sets up a processing mode. For example, the release of dopamine seems to select and enhance the activities of prefrontal and striatal systems involved in the pursuit or switching of goals, in response to expectancies of reward. In fact, the ACC is a primary target of dopamine release (Paus, 2001). At the same time, dopamine inhibits cortical (and striatal) firing through its impact on inhibitory neurons. This might mean that directed cognitive and motor responses require the inhibition of alternative responses. Each of the neuromodulators sets the cortex in a mode of operation that enhances some activities and suppresses others, and neuropeptides set both the body and the brain in a particular action mode concerning territory, nurturance, sex, aggression, and other mammalian agendas (Panksepp, 1998). Thus, brainstem neuromodulatory release provides a powerful regulating influence on all higher-brain systems, controlling arousal, mood, activity level, sleep, action orientation, attentional focus, and the quality and efficiency of all cognitive operations. Perhaps the best argument for the regulatory aspects of these chemicals is that animals (including humans!) self-administer substances that enhance their action. That seems to epitomize self-regulation.

Other regulatory influences originate in the brain stem, including perceptual orientations mediated by nuclei in the midbrain (e.g., the superior and inferior colliculi). Although visual information processing is controlled by the cortex in humans, brainstem nuclei influence this processing by highlighting sensory cues before they reach the cortex. Nuclei in the brain stem and HTh also receive input from the interior of the body. Proprioceptive and enteroceptive information from the muscles, organs, skin, and joints, carried directly by the autonomic nervous system and indirectly via hormones in the bloodstream, are all registered by brainstem and hypothalamic nuclei. Because these nuclei "perceive" and reciprocally control bodily changes, they mediate bodily sensations, which both feedback to bodily control processes and ascend to higher-order brain systems such as the amygdala and certain cortical areas (e.g., the insula). These sensations may well be the stuff of rudimentary emotional feelings, which have the potential to massively affect cognitive activities ranging from attentional orientation to emotional consciousness (Damasio, 1999; Panksepp, 1998; Thayer & Lane, 2000). Information ascending from the brain stem is also processed by the hypothalamus in relation to drive states (hunger, thirst, sex). Computations about need versus satisfaction adjust the pursuit of goal states through connections from the hypothalamus directly to components of the ventral striatum (e.g., the nucleus accumbens) (Stratford & Kelley, 1999). In turn, the striatum is connected to the thalamus and motor cortex.

Primitive emotional response circuits, such as those controlling rage and fear, are active within the PAG and hypothalamus. Although their activity is often driven by associations mediated by the amygdala (basic emotional conditioning), they also feedback to the amygdala, which then influences cortical processes directly. Amygdala activity directs the pickup of sensory information in the posterior cortex (LeDoux, 1995), it influences attention and self-monitoring in the ACC as already noted, and it is densely connected with OFC regions that mediate the animal's expectancies in relation to the rewarding or punishing aspects of the environment (Rolls, 1999). Pathways from the AM also project to the striatum (nucleus accumbens and ventral tegmental area), enhancing activation of both these systems on the basis of emotional associations (Cardinal, Parkinson, Hall, & Everitt, 2002).

Taken together, the activities of subcortical structures arrayed along the neuroaxis have profound effects on each other and on cortical processes. These activities can be instrumental in initiating patterns of coordination that are explicitly regulatory. The upward or "ascending" direction of regulation does not imply deliberate, executive control, consciousness, or decision-making. Rather, it conveys the power of basic emotional states, needs, drives, and bodily sensations to influence all mental activity. This is regulation according to relevance—regulation of sophisticated executive processes by the registration and processing of environmental cues and organismic requirements. Moreover, because the flow of activity is almost always reciprocal, and vertical integration rapidly gives rise to whole-brain patterns of coordination, these upward regulatory effects are sure to feedback down to the lower levels of the neuroaxis to form global constellations that truly constitute a self-regulating brain.

Again, if self-regulation means regulation not only *of* a self but also *by* a self, then what kind of "self" characterizes these primal regulatory functions? Earlier we mentioned that intelligent action results from our capacity to override emotional impulses through functions such as planning, set shifting, context-updating, and so forth, mediated by the influence of cortical controls over subcortical processes. Intelligent action is something we humans are proud of. It is the basis of the self we like. But the front section of one's daily newspaper suggests that intelligent action is a rare commodity. Various forms of slaughter arise all over the world because of the impulsive appraisals, emotions, and action tendencies that direct human behaviour, not only in the moment but sometimes for hours or days at a time. In fact, these impulses or settings can be shaped and honed through religious training and other institutions that highlight human differences. Whether we examine cruelty to pets or children or the tendency to vote for politicians who best elicit our basest hopes and fears, we are likely to conclude that motivational urges get out of hand. Cortical mechanisms of self-regulation do not always override them. And when the brain stem or the amygdala are calling the shots, then attention, perception, thought and action are driven by needs, concerns, attractions, and other urges that have not been sculpted by deliberate learning or intelligence.

If we ascribe intentionality only to higher-order brain systems—those fundamental to judgment and decision-making—then we might conclude that when people harm their pets or their children they are acting without intentionality, without a self. This seems wrong. One advantage of the present analysis is that, by stipulating different epicenters of self-regulation, we can consider the possibility of different epicenters of self, associated with different levels or different kinds of intentional action. The thoughtful self, wielding an overarching, conscious intentionality, perhaps mediated by interconnections among the ACC, DLPFC, and HPC, may take a back seat much of the time. This self may be replaced by another, very coherent self who is motivated, poised for action, steeped in a history of unconscious associations, and whose emotions, goals, and drives are vibrant sources of intentionality. This self might be mediated by interconnections among the ventral striatum, AM, HTh, and midbrain (upper brain stem)—connections that harness all other brain regions in a massively coherent coordinative pattern that directs attention and action. Thus, even Freeman's notion of a global, unitary intentionality might be compatible with sources of self-regulation located at lower levels of the neuroaxis. The intentionality that emerges from these sources of activation may not avoid rationality but rather use it to accomplish irrational ends.

Given the dramatic differences between upward and downward directions of neural self-regulation, and given the inevitability that these two streams become at least partially synchronized in the process of vertical integration, the most comprehensive, neurally based perspective on self-regulation may come from studying feedback between these directions of influence. Metaphorically, vertical feedback processes might appear like eddies in a stream where two directions of flow give rise to whirlpools with their own unique and enduring structure. Feedback relations among neural structures have been mapped out in detail elsewhere (Lewis, 2005a). For now, however, we can examine a model system that epitomizes the tight coupling between upward and downward regulation. This loop includes massive connections from the AM to the ventral (rostral) ACC and strong connections from the dorsal (caudal) ACC back to the AM. Because the ventral and dorsal ACC are themselves positively connected, high activation in ventral ACC, triggered by AM arousal, may generally activate inhibitory signals from dorsal ACC back to the amygdala (Pezawas et al., 2005). These inhibitory connections may in turn attenuate AM activity, thus regulating negative emotions and appraisals.

This feedback model helps explain the negative correlation between dorsal ACC activity and AM activation—a correlation with explicit emotional concomitants. More "cognitive" tasks increase dorsal ACC activity and reduce AM activity, whereas sad or anxious mood states correspond with greater AM and ventral ACC activity and reduced dorsal ACC responsiveness (Bush et al., 2000; Drevets, 2000; Drevets & Raichle, 1998). But what is particularly interesting about this loop is that individual differences in the activity of its components correspond with clinical differences based on the quality or style of self-regulation. Normal individuals appear to use ACC feedback to modulate AM arousal, even while the AM is directing prefrontal patterns of attention and anticipation. This "eddy" of self-regulation may generally be very useful. However, depressed or anxious individuals show increased ventral ACC activity (corrected for volumetric differences – Drevets, 2000), enhanced AM arousal, and in some studies reduced dorsal ACC activity (see Drevets, 2000, for a review). These individuals are also more likely to show a genetic anomaly in a serotonin transporter gene, suggesting the under-utilization of serotonin in ACC neurons (Pezawas et al., 2005). Thus, whereas normal individuals can utilize dorsal ACC inhibitory circuitry to regulate negative states, depressed individuals may have a disconnect between ventral and dorsal ACC systems, allowing them to be dominated by an amygdala that regulates cortical activity on the basis of learned negative associations. It is this subcortical source of self-regulation (centered in the AM) that is often tossed off as an *absence* of self-regulation. However, individuals showing this genetic variation and accompanying neural features tend to be trait anxious (Pezawas et al., 2005). They are cautious and controlled, and they show limited spontaneity. Clearly these individuals are not lacking self-regulation; rather, they display a style of self-regulation that is different and generally considered maladaptive.

Before moving on to a developmental analysis, it is worth noting that diverse epicenters of self-regulation might exist in the same person at the same time with greater or lesser degrees of synchrony. For example, one could be utilizing ACC activity to control one's impulses carefully and deliberately during rush hour, attempting to pick an efficient route home while redirecting emotions of frustration and anxiety. At the same time, or intermittently, an AM-mediated anxious appraisal about the importance of being on time for dinner may regulate cognitive and motor activity, instilling a certain amount of risk-taking in the service of a prepotent agenda. In this example, two epicenters of self-regulation may alternate or interface in a relatively harmonious way, such that both work in a complementary fashion to achieve an effective response to the challenges posed by the environment. However, in many familiar situations, subcortical epicenters of self-regulation remain dominant for extended periods. When women become mothers, they often speak of "losing their minds" with the intensity of attachment-related drives and behaviours. Perhaps they haven't lost their minds as much as yoked them to the regulatory controls of the hypothalamus. Extended states of love, need, addiction, and other basic agendas must subjugate flexible decision-making in order to maintain their hold on behaviour. Furthermore, in some personality patterns and psychopathologies, higher and lower epicenters of self-regulation might be badly out of whack. An oscillation between periods of black anger, leading to violence or abuse, and periods of intense self-control, marked by a lack of spontaneity, insight, or empathy, might characterize an aggressive personality disorder. One might also consider bipolar disorders as exemplifying disparate epicenters of self-regulation—the over-confident sense of personal power and the depressive sense of doom—that remain out of sync with each other.

There is much more theoretical work to do here, but an important direction for modeling might involve the embedding of a habitual epicenter of self-regulation within a given cerebral hemisphere. Coordination can be much greater within than between hemispheres, allowing each hemisphere to serve as a quasi-independent source of intentionality, interpretation, and action. A disjunction between the hemispheres in terms of self-regulation may fit well with evidence of behavioural anomalies (e.g., the gnosias) resulting from asymmetric brain damage. We would expect the right hemisphere to lend itself more fully to self-regulation centered in connections between the cortex and limbic system, consistent with evidence of greater connectivity between right PFC and limbic structures (Bear, 1983; Tucker, 1992). The left hemisphere, in turn, may lend itself to regulatory activities centered in connections between the ACC and dorsolateral PFC, whereby deliberate planning and decision-making can be exercised even in the face of intense emotional challenges. Interestingly, given the critical role of the cortex in consciousness, this partitioning of self-regulatory processes might manifest as a sense of two selves, one more mature and rational and the other more childish and demanding. This sense of disunity is very often reported, both in the therapist's office and in intimate conversation. We will later speculate on how each of these selves might develop in a somewhat independent manner, and how their complementarity might point to critical individual differences in mental health.

4. Development of cortical versus subcortical sources of self-regulation

4.1. Developmental course of ACC-mediated self-regulation

The developmental study of neural systems implicated in self-regulation is really just getting underway, and very little research has been done on the developmental timetable of changes in cortical or subcortical systems of self-regulation. However, developmental neuroscientists have acquired a pastiche of behavioural and neurobiological findings. Through inference from adult studies, behavioural milestones, developmental logic, and some good guessing, they have begun to propose reasonable models of developmental change in cortical controls. Because we have focused our attention on the ACC as a hub of brain systems mediating effortful, deliberate, or conscious self-regulation, we now present theory and findings on the development of ACC-mediated self-regulation.

Thanks to recent longitudinal neuroimaging studies (Giedd et al., 2004; Gogtay et al., 2004), we now know that more dorsal and lateral regions of the prefrontal cortex continue to mature from late infancy through adolescence (Gogtay et al., 2004). Correspondingly, the capacity for effortful and deliberate self-regulation strategies also develops continuously across these years. This developmental trajectory is not entirely linear, however. For example, children make major leaps in the capacity for deliberate and effortful control, rapidly achieving a number of new skills between the ages of 3 and 6 years. Although there is little direct data on the neural correlates of effortful control in very young children, the development of effortful self-regulation processes is thought to be mediated by dorsal ACC networks that come on line between the ages of 3 and 6 (Posner & Rothbart, 2000). During this period children become better able to delay gratification (Prencipe & Zelazo, 2005; Thompson et al., 1997), deliberately control impulsive behaviour (Jones, Rothbart, & Posner, 2003), use higher-order rule systems for decision-making (Zelazo & Mueller, 2002), and achieve higher levels of explicit emotional awareness (Lane & McRae, 2004). All of these skills may depend on the action-monitoring functions associated with the ACC. Also in this age range, a more general capacity for prefrontally-mediated social understanding may be enhanced by the capacity for conscious perspective-taking, leading to the well-known onset of children's understanding that others' knowledge and beliefs differ from their own (Astington, 1994). This suite of executive abilities, presumably mediated by the ACC and related circuitry, may be the developmental outcome of an emergent cortical epicenter of self-regulation. In fact, the emergence of this source of self-regulation, now accessible in response to situational demands, may provide the child with his or her first experiences of mastery over the subcortical sources of self-regulation that have characterized neural functioning up until now.

Several experimental paradigms have been developed to tap the neural correlates of deliberate executive function in school-age children and adolescents. These paradigms usually require effortful attention to override a strong prepotent response or choose between conflicting responses, thus implicating ACC-mediated action-monitoring. Examples include go/no-go tasks, in which participants must press a button but occasionally withhold a button press, overriding the automatic impulse to press; Stroop tasks, in which participants are shown coloured words and must override the impulse to read the word in order to respond to its colour; and Flanker tasks, in which participants have to ignore misleading cues in order to identify the direction of a stimulus. Such tasks are thought to tap attentional and emotional self-regulation, or effortful control, as reflected by activation of the dorsal ACC. However, neuroimaging methods that can capture this activity directly have seldom been used on populations of young children. Instead, ACC activity is often inferred from the measurement of neurophysiological signatures of cortical processes. Event-related potentials (ERPs) are event-locked EEG waves averaged over many trials, and ERP waveforms show predictable patterns following a given stimulus or response. One well-researched ERP component associated with effortful self-regulation is the N2. The N2 is a negative peak found at frontal-midline electrodes roughly 200–400 ms after the presentation of a stimulus, and it is generally thought to be generated by prefrontal regions that include the dorsal ACC (e.g., Bokura, Yamaguchi, & Kobayashi, 2001; Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003; Tucker et al., 2003; van Veen & Carter, 2002). Very little research has examined relations between the N2 and the cognitive skills required to override prepotent response tendencies in children. However, in our own research with children, N2 amplitudes have been associated with measures of emotion regulation (Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006; Lewis, Todd, & Honsberger, 2007; Todd, Lewis, Meusel, & Zelazo, under review), measures of executive function (Lamm, Zelazo, & Lewis, 2006), and behavioural indices of flexible interpersonal behaviour (Lewis, Granic, & Lamm, 2006). Three of these studies are briefly reviewed next.

In a study of effortful self-regulation processes in 4–6-year-old children, we showed participants pictures of angry and happy faces as stimuli in a go/no-go task (Todd et al., under review). After about one second, a frame appeared around the face. At that point, depending on the colour of the frame, children pressed a button or withheld a response. When children pressed the button both the face and frame disappeared. Children showed the largest N2s following angry faces in no-go trials, suggesting that greater effortful regulation was required when they had to withhold the impulse to make the face go away, particularly when the face was angry. Models of cortical sources of scalp activation suggested a dorsal cingulate region that was most active following angry faces. This model is consistent with the conclusion that, by the age of 5, children are able to recruit dorsal cingulate systems to consciously override an impulsive response.

In a second study, 5–16 year-olds were engaged in an affectively charged go/no-go task (Lewis, Lamm, et al., 2006). The N2 component was apparent for all ages, but was found to show a linear decrease in amplitude over age, that is, across five waves from early childhood to adolescence. This suggested more efficient information processing in circuits involving the ACC as children developed (e.g., Casey et al., 1997). Models of cortical sources suggested that both older and younger children used dorsal as well as ventral circuits to generate the N2 and related scalp activity. However, older children showed more anterior cingulate activity and younger children showed more posterior cingulate activity. Measures of response time and accuracy indicated that older children also performed the task more efficiently. Thus, development through middle childhood might be characterized by increasing efficiency in the activity of dorsal ACC systems associated with effortful self-regulation.

A third study looked at the relationship between behavioural flexibility and N2 amplitudes in a group of children referred for treatment for antisocial behaviour (Lewis, Granic, & Lamm, 2006). In this study, parent–child interactions were videotaped in the home. The interactions included a discussion of an unresolved problem that was designed to elicit negative emotion. Videotapes were coded for affect, and measures of emotional flexibility within parent–child interactions were assessed for the problem-solving discussion. The same children underwent an ERP task in the lab, where the frontal N2 was elicited in a go/no-go task that included a negative mood induction. We then examined associations between behavioural flexibility in the problem-solving discussion and N2 amplitudes. Results showed that greater behavioural flexibility predicted larger-amplitude N2s following the negative mood induction, suggesting greater recruitment of frontocortical control systems in children with more flexible self-regulation styles. Moreover, source models indicated a generator for the N2 in the midline region of the prefrontal cortex, corresponding to the ACC, but only for children showing the highest levels of flexibility (Fig. 3). These results suggest greater ACC-mediated regulation of a response repertoire for children who manage to maintain flexible interpersonal interactions despite the experience of negative emotions.Taken together, results from these studies are consistent with the notion that, by 4–6 years, children can recruit dorsal cingulate areas for the regulation of cognitive and emotional functions in social contexts. However, frontalization—the finding of more frontal activity in older children—and increasing cortical efficiency continue into adolescence as children refine their self-regulation skills (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 1997; Luna & Sweeney, 2004; Luna et al., 2001; Rubia et al., 2000). These observations suggest that younger children tend to rely on more automatic posterior and ventral systems of

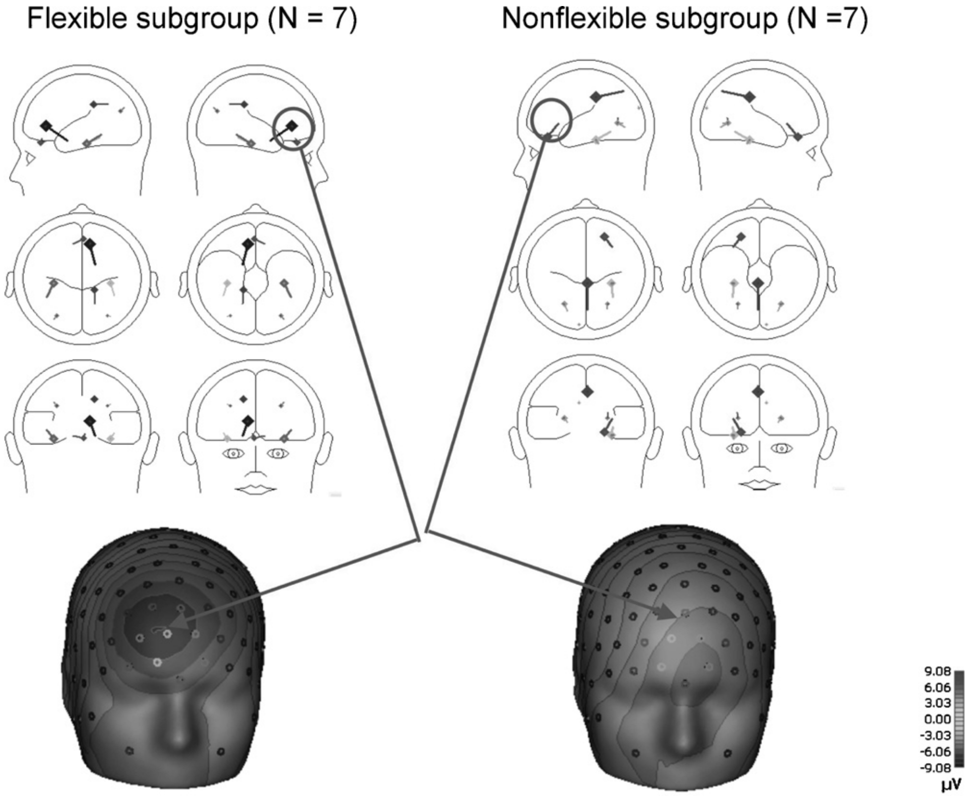

Fig. 3. Antisocial children who showed the highest levels of behavioural flexibility in interactions with parents showed greater frontal scalp activations, associated with self-regulation, in a go/no-go task following a negative mood induction. Here we used patterns of scalp activation to model the cortical generators of the N2 for the 7 most flexible and 7 least flexible children in our sample. The model shows a source in the region of the ACC, active only in the more flexible children.

control while older children increasingly recruit more sophisticated prefrontal systems, including networks centered on the dorsal ACC. Behavioural studies also suggest that the more complex the self-regulation task, and the more it taps complex rule use associated with dorsal prefrontal cortex, the more extended its developmental trajectory (Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Kesek, Zelazo, & Lewis, in press). In fact, activity in dorsal and lateral prefrontal regions, associated with working memory and manipulation of information, has been shown to increase through adolescence (e.g., Kwon, Reiss, & Menon, 2002). Thus, regulation strategies that involve long-term or contingent planning, or sophisticated reappraisal of context, take the longest to develop. At the same time, hormonal changes, complex and intense social relationships, conflicts with parents, and the lure of substance abuse and risky behaviour pose increasing challenges to teenagers' developing capacities for effortful self-regulation. Indeed, the *gradual* development of dorsal ACC networks, when juxtaposed with the *rapid* increases in emotional reactivity associated with puberty, may go a long way toward explaining many of the challenges adolescents face when they have to think their way through intense emotional experiences.

4.2. Development of amygdala-mediated self-regulation

We have described a number of subcortical systems that perform regulatory functions, from the brain stem to the limbic system. However, structures below the limbic system (and striatum) along the neuroaxis show very little change with development, and the change that they do show concerns the sensitivity and responsiveness of cell groups to various inputs. In other words, developmental change in these systems does not pertain to the content or complexity of information processing, and thus we would not ordinarily describe them as learning through experience. However, limbic structures are highly plastic, and their plasticity is the hallmark of their function. The hippocampus and amygdala exemplify this plasticity, with the HPC acquiring synapses that mediate episodic and semantic memory and the AM acquiring synapses that mediate associative memory. The AM's associative learning is central for assigning emotional significance to objects and events. Hence, we will examine AM-mediated learning as a paradigm case of developmental change in subcortical sources of self-regulation.

Cole et al. (2004) highlighted two meanings of emotion regulation: emotion as regulated and emotion as regulating. In studies examining interactions between the AM and other neural systems, it is almost always the AM that is being regulated (e.g., by ACC, OFC, and other cortical systems) rather than doing the regulating, in keeping with the first of Cole et al.'s definitions. Neurodevelopmental research has done little to rectify this imbalance, mainly because the *function* of the AM seems to change little with development whereas the functions of cortical systems change in rather obvious ways. Nevertheless, researchers who take a "functionalist" approach to emotional development have emphasized for years that emotions organize development through their impact on psychological processes in real time (e.g., Barrett & Campos, 1987). For them, the function of emotions is to regulate other psychological processes—most notably cognition, including attention and perception—in order to move the organism toward the achievement of goals that are highlighted by emotional states. The amygdala, by encoding the emotional meaning of events, must play a major role in this process. But to get a sense of how amygdalar processes change with and contribute to development, the most fruitful source of information may not be developmental research but research on the neurobiology of clinical disorders related to anxiety, such as post-traumatic stress disorder (PTSD).

Anxiety disorders are understood to arise when emotional associations are consolidated through synaptic connections formed in the amygdala due to traumatic or poorly understood threat experiences. Brewin (2001) summarizes considerable research suggesting that, in the case of PTSD, emotional memories mediated by the AM can control an individual's appraisal and response tendencies for an entire lifespan, particularly when hippocampally mediated episodic memories cannot easily be accessed to contextualize these associations. Circuitry both within the AM and between the AM and other neural systems (e.g., OFC, posterior cortex) continues to be modified by events construed as threatening, so that impulsive reactions to these events (e.g., escape) take an ever-greater hold on the repertoire of available responses. However, even for non-clinical anxiety, the AM has considerable power to regulate the development of corticolimbic processes. Through direct pathways to the HPC, the AM highlights particular interpretations, memories, and appraisals, which then become increasingly consolidated over time (Pare, Collins, & Pelletier, 2002). Thus, emotional associations mediated by the AM not only regulate real-time cortical activity but also sculpt developmental trajectories by which events acquire lasting meanings.

Anxiety is not the only emotional state that demonstrates the AM's power to regulate other systems. Anger and rage reactions, mediated by the lateral AM in the presence of a sexual rival or intruder, set up a long-lasting state of "aggressive arousal" which changes the probability and time course of ongoing aggressive behaviour (Potegal, Hebert, DeCoster, & Meyerhoff, 1996). However, because the AM also learns who is a rival and who is not, the regulatory impact of aggressive arousal on behaviour is sure to change with experience. Previously, we discussed some of the circuitry in which the AM participates with lower structures to harness neuromodulators and other bottom–up regulatory influences. What is important for now is that these real-time activities establish and strenghen recurrent appraisals and response tendencies—in a word, meanings—by triggering coordinative patterns across multiple corticolimbic systems differently over development. The epicenter of these coordinative patterns may be an amygdala which itself changes with development.

Associative memories mediated by the AM, and for that matter episodic and semantic memories mediated by the HPC, lay down patterns of meaning that continue to be refined or sculpted over development. Because these limbic structures are plastic and sensitive to experience, they harness the cortex to the content and meaning of events as they change with development. Thus, limbic epicenters of self-regulation have a particular role to play in development: they modulate thought, perception, planning, and decision-making activities in the cortex, on any given occasion, according to the ongoing accumulation of experience itself. They update what we know of the content of the world, providing a basis for the deliberate, executive processes carried out by cortical systems such as the ACC. Because the meaning of events is always, to at least some degree, emotional, this source of self-regulation can be thought of as motivationally oriented. Limbic centers direct and focus cortical activities on objects and events that demand action—in other words, that are motivationally relevant. At the same time, cortical sources of self-regulation continue to become more powerful, efficient, or effective over development, in order to deal with these objects and events in increasingly intelligent ways.

We have emphasized that the assignment of meaning to objects, people, and events changes with development. In fact, some theorists point to the extended plasticity of limbic structures over long periods of developmental time as a means for ensuring that individuals remain permeable and adaptive over the lifespan (Barbas, 1995). However, synaptic networks centered around limbic structures also acquire an inevitable inertia. As new synapses are formed and strengthened, others are pruned and discarded. Hence, meanings built up in these limbic networks acquire permanence over time, providing continuity to personal experience. The meanings and values we attach to events in the world become familiar; they become who we are. The cumulative nature of the response tendencies initiated through limbic self-regulation ensures the *consolidation of habits* of appraisal, emotion, and behaviour within developmental trajectories. Elsewhere we have discussed these habits as *emotional interpretations* (EIs; Lewis, 2005a, 2005b; Lewis & Todd, 2005). But they are understood by other theorists using other constructs (e.g., Izard, 1984; Malatesta & Wilson, 1988). Whatever they are to be called, they constitute the components of personality development in normal individuals and developing psychopathologies in those with more serious difficulties.

Although there is a cumulative buildup of corticolimbic habits over development, adolescence serves as a transitional period during which individual regulation styles can either become more consolidated or shift radically. While cortical connectivity underlying effortful regulation processes continues to develop gradually (for a review see Paus, 2005), and connectivity between prefrontal and limbic regions increases (Spear, 2000), subcortical motivational systems that focus attention on social and sexual rewards are also ramped up during puberty (for a review see Spear, 2003). In addition, changes to dopaminergic systems may play a role in increasing reward-seeking and risk-taking behaviour (Spear, 2003). The developmental lag between earlier subcortical enhancement of motive states and later maturation of cortical control systems has been famously described as starting the car without a skilled driver at the wheel (Dahl, 2001). At the same time, emergence into a wider social world dominated by peer relationships, and increased conflicts with parents, provide external challenges to the balance between cortical and subcortical epicenters of self-regulation.

It is not surprising that patterns of psychopathology often emerge in adolescence, when imbalances between dorsal and ventral ACC systems may become exacerbated and entrenched. For example, a shy inhibited child may become more isolated and anxious at puberty as feelings of social inadequacy hijack ventral cortical processes in the service of rumination. Increased sexual drive may combine with feelings of unattractiveness to reinforce a sense of self-hatred and strategies of social avoidance. In this case a trajectory of anxiety and depression can become entrenched as connections between the amygdala and ventral ACC are reinforced (Heinz et al., 2005) and those between dorsal ACC and the amygdala are attenuated. Alternatively, a teenager might effortfully override impulses toward avoidance, seek out a wider range of social situations, and develop a constellation of more positive social appraisals and relationships. In this case she seeks out contexts that pull for fewer of the negative emotions that might otherwise overwhelm dorsal control systems. Here, dorsal and ventral ACC circuits may remain more resilient and interconnected, allowing dorsal control systems to develop in tandem with changing motivational drives. By the end of adolescence, the balance of several epicenters of self-regulation, underlying a unique repertoire of emotional interpretations, is largely in place, defining the personality style of the young adult.

5. Conclusion

This article has explored new avenues for understanding the concept of self-regulation inspired by a close look at the flows of activity and modes of interaction among neural components. We have argued that a neural perspective demands the abandonment of categorical delineations between cognition and emotion, as well as the acknowledgement of multiple sources and directions of self-regulation, whereby different brain systems tune each other in the service of global synchrony and coherence. Two important self-regulatory patterns were described: (1) regulation of more automatic responses by dorsal ACC systems mediating deliberate, executive control, and (2) regulation of cortical processes, responsible for the intelligent organization of behaviour, by subcortical structures that modulate the emotional significance of assigned meanings. We have speculated that these two regulatory processes, each fanning out from a different neural epicenter of self-regulation, might coexist and balance one another when individuals behave in ways that are motivationally relevant yet sensible and planful. We have also demonstrated how both sources of regulation change with development—one becoming more powerful, efficient, and flexible, the other consolidating the meanings of things into a continuous stream of personal significance.

We end this discussion with one final speculation: If these epicenters of self-regulation can be more or less balanced in real time, working together to achieve greater or lesser degrees of appropriate functioning, can they also grow in parallel over development in a more or less balanced fashion? An optimal balance might be characterized by cortical controls that rein in, but don't paralyze, the impulses and limbic controls that focus attention and perception—thus keeping the individual tuned to what is personally salient but open to alternative interpretations. If there is an optimal balance, then different kinds of psychopathology might reflect different kinds of imbalance between the development of cortical and subcortical epicenters of regulation. Excessive cortical self-regulation might be manifested in over-control, resulting in a utilitarian and emotionally vacuous approach to life. In contrast, excessive subcortical self-regulation might take the form of a highly impulsive mode in which personal meanings, needs, passions, and fears dominate behaviour at the expense of thoughtful deliberation. The notion of multiple levels of self-regulation can provide a valuable tool for understanding the development of individual differences and psychopathologies associated with specific patterns of balance or imbalance among neural epicenters. We hope to take these ideas further in subsequent theoretical work.

References

Allman, J., Hakeem, A., Erwin, J. M., Nimchinsky, E., & Hof, P. (2001). The anterior cingulate cortex: The evolution of an interface between emotion and cognition. In A. R. Damasio & A. Harrington (Eds.), *Unity of knowledge: The convergence of natural and human science. Annals of the New York Academy of Sciences* (pp. 107–117). New York: New York Academy of Sciences.

Amodio, D. M., & Frith, C. D. (2006). Meeting of minds: The medial frontal cortex and social cognition. *Nature Reviews Neuroscience*, *7*, 268–277.

Astington, J. W. (1994). *The child's discovery of the mind*. London: Fontana.

Barbas, H. (1995). Anatomic basis of cognitive-emotional interactions in the primate prefrontal cortex. *Neuroscience & Biobehavioural Reviews*, *19*, 449–510.

Barrett, K. C., & Campos, J. J. (1987). Perspectives on emotional development II: A functionalist approach to emotions. In J. D. Osofsky (Ed.), *Handbook of infant development* (pp. 555–578). New York: Wiley.

Bear, D. M. (1983). Hemispheric specialization and the neurology of emotion. *Archives of Neurology*, *40*, 195–202.

Bokura, H., Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/NoGo task. *Clinical Neurophysiology*, *112*, 2224–2232.

Brewin, C. R. (2001). A cognitive neuroscience account of posttraumatic stress disorder and its treatment. *Behaviour Research and Therapy*, *39*, 373–393.

Buck, R. (1999). The biological affects: A typology. *Psychological Review*, *106*, 301–336.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*, 301–311.

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

Cardinal, R. N., Parkinson, J. A., Hall, J., & Everitt, B. J. (2002). Emotion and motivation: The role of the amygdala, ventral striatum, and prefrontal cortex. *Neuroscience and Biobehavioural Reviews*, *26*, 321–352.

Case, R., Okamoto, Y., Griffin, S., McKeough, A., Bleiker, C., Henderson, B., et al. (1996). The role of central conceptual structures in the development of children's thought. *Monographs of the Society for Research in Child Development*, *61* (Serial No. 246).

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

Cole, P. M., Martin, S. E., & Dennis, T. A. (2004). Emotion regulation as a scientific construct: Methodological challenges for child development research. *Child Development*, *75*, 317–333.

Critchley, H. D., Mathias, C. J., Josephs, O., O'Doherty, J., Zanini, S., Dewar, B.-K., et al. (2003). Human cingulate cortex and autonomic control: Converging clinical and neuroimaging evidence. *Brain*, *126*, 2139–2152.

Crone, E. A., Ridderinkhof, K. R., Worm, M., Somsen, R. J. M., & van der Molen, M. W. (2004). Switching between stimulus-response mappings: A developmental study of cognitive flexibility. *Developmental Science*, *7*, 443–455.

Dahl, R. E. (2001). Affect regulation, brain development, and behavioral/emotional health in adolescence. *CNS Spectrums*, *6*, 60–72.

Damasio, A. R. (1999). *The feeling of what happens: Body and emotion in the making of consciousness*. Fort Worth, TX: Harcourt College Publishers.

Davidson, R. J., Putnam, K. M., & Larson, C. L. (2000). Dysfunction in the neural circuitry of emotion regulation: A possible prelude to violence. *Science*, *289*, 591–594.

Drevets, W. C. (2000). Neuroimaging studies of mood disorders. *Biological Psychiatry*, *48*, 813–829.

Drevets, W. C., & Raichle, M. E. (1998). Reciprocal suppression of regional cerebral blood flow during emotional versus higher cognitive processes: Implications for interactions between emotion and cognition. *Cognition and Emotion*, *12*, 353–385.

Eisenberg, N., Fabes, R. A., Murphy, B., Karbon, M., Smith, M., & Maszk, P. (1996). The relations of children's dispositional empathy-related responding to their emotionality, regulation, and social functioning. *Developmental Psychology*, *32*, 195–209.

Freeman, W. J. (1995). *Societies of brains: A study in the neuroscience of love and hate*. Hillsdale, NJ: Erlbaum.

Freeman, W. J. (1999). *How brains make up their minds*. London: Weidenfeld & Nicolson.

Freeman, W. J. (2000). Emotion is essential to all intentional behaviours. In M. D. Lewis & I. Granic (Eds.), *Emotion, development and self-organization: Dynamic systems approaches to emotional development* (pp. 209–235). New York: Cambridge University Press.

Frijda, N. H. (1986). *The emotions*. Cambridge: Cambridge University Press.

Frijda, N. H. (1993). The place of appraisal in emotion. *Cognition and Emotion*, *7*, 357–387.

Frith, C. D., Friston, K., Liddle, P. F., & Frackowiak, R. S. (1991). Willed action and the prefrontal cortex in man: A study with PET. *Proceedings of the Royal Society of London, Serial B Biological Science*, *244*, 241–246.

Gemba, H., Sasaki, K., & Brooks, V. B. (1986). "Error" potentials in limbic cortex (anterior cingulate area 24) of monkeys during motor learning. *Neuroscience Letters*, *70*, 223–227.

Giedd, J. N., Rosenthal, M. A., Rose, A. B., Blumenthal, J. D., Molloy, E., Dopp, R. R., et al. (2004). Brain development in healthy children and adolescents: Magnetic resonance imaging studies. In M. S. Keshaven, J. L. Kennedy, L. James, & R. M. Murray (Eds.), *Neurodevelopment and schizophrenia* (pp. 35–44). New York: Cambridge University Press.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences*, *101*(21), 8174–8179.

Goldberg, G. (1985). Supplementary motor area structure and function: Review and hypotheses. *Behavioural and Brain Sciences*, *8*, 567–616.

Heinz, A., Braus, D., Smolka, M. N., Wrase, J., Puls, I., Hermann, D., et al. (2005). Amygdala-prefrontal coupling depends on a genetic variaton of the seratonin transporter. *Nature Neuroscience*, *8*, 20–21.

Izard, C. E. (1984). Emotion-cognition relationships and human development. In C. E. Izard, J. Kagan, & R. B. Zajonc (Eds.), *Emotions, cognition and behaviour* (pp. 17–37). Cambridge: Cambridge University Press.

Izard, C. E. (1993). Four systems for emotion activation: Cognitive and noncognitive processes. *Psychological Review*, *100*, 68–90.

Johnson, M. H. (1999). Cortical plasticity in normal and abnormal cognitive development: Evidence and working hypotheses. *Development and Psychopathology*, *11*, 419–437.

Johnson, M. H. (2000). Functional brain development in infants: Elements of an interactive specialization framework. *Child Development*, *71*, 75–81.

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

Keil, A., Gruber, T., Muller, M. M., Moratti, S., Stolarova, M., Bradley, M. M., et al. (2003). Early modulation of visual perception by emotional arousal: Evidence from steady-state visual evoked brain potentials. *Cognitive and Affective Behavioural Neuroscience*, *3*, 195–206.

Kesek, A., Zelazo P. D., & Lewis, M. D. (in press). The development of executive function and emotion regulation in adolescence. In N. Allen & L. Sheeber (Eds.), *Adolescent emotional development and the emergence of depressive disorders*. New York: Cambridge University Press.

Kwon, H., Reiss, A. L., & Menon, V. (2002). Neural basis of protracted developmental changes in visuospatial working memory. *Proceedings of the National Academy of Sciences*, *99*, 13336–13341.

Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia*, *44*, 2139–2148.

Lane, R. D., & McRae, K. (2004). Neural substrates of conscious emotional experience: A cognitive neuroscience perspective. In M. Beauregard (Ed.), *Consciousness, emotional self-regulation and the brain* (pp. 87–122). Amsterdam: John Benjamins.

Lane, R. D., Reiman, E. M., Axelrod, B., Yun, L., Holmes, A., & Schwartz, G. E. (1998). Neural correlates of levels of emotional awareness: Evidence of an interaction between emotion and attention in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, *10*, 525–535.

LeDoux, J. E. (1995). In search of an emotional system in the brain: Leaping from fear to emotion and consciousness. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1049–1061). Cambridge, MA: MIT Press.

Lewis, M. D. (2005a). Bridging emotion theory and neurobiology through dynamic systems modeling (target article). *Behavioral and Brain Sciences*, *28*, 169–194.

Lewis, M. D. (2005b). Self-organizing individual differences in brain development. *Developmental Review*, *25*, 252–277.

Lewis, M. D., & Granic, I. (1999). Self-organization of cognition-emotion interactions. In T. Dalgleish & M. Power (Eds.), *Handbook of cognition and emotion* (pp. 683–701). Chichester, England: Wiley.

Lewis, M. D., Granic, I., & Lamm, C. (2006). Behavioral differences in aggressive children linked with neural mechanisms of emotion regulation. *Annals of the New York Academy of Sciences*, *1094*, 164–177.

Lewis, M. D., Lamm, C., Segalowitz, S. J., Stieben, J., & Zelazo, P. D. (2006). Neurophysiological correlates of emotion regulation in children and adolescents. *Journal of Cognitive Neuroscience*, *18*, 430–443.

Lewis, M. D., & Todd, R. M. (2005). Getting emotional: A neural perspective on emotion, intention and consciousness. *Journal of Consciousness Studies*, *12*, 210–235.

Lewis, M. D., Todd, R. M., & Honsberger, M. (2007). Event-related potential measures of emotion regulation in early childhood. *NeuroReport*, *18*, 61–65.

Luna, B., & Sweeney, J. A. (2004). Cognitive development: Functional magnetic imaging studies. In M. S. Keshaven, J. L. Kennedy, L. James, & R. M. Murray (Eds.), *Neurodevelopment and schizophrenia* (pp. 35–44). New York: Cambridge University Press.

Luna, B., Thulborn, K., Munoz, D. P., Merriam, E. P., Garver, K. E., Minshew, N. J., et al. (2001). Maturation of widely-distributed brain function subserves cognitive development. *NeuroImage*, *13*, 786–793.

Luu, P., & Tucker, D. M. (2002). Self-regulation and the executive functions: Electrophysiological clues. In A. Zani & A. M. Preverbio (Eds.), *The cognitive electrophysiology of mind and brain* (pp. 199–223). San Diego: Academic Press.

Malatesta, C. Z., & Wilson, A. (1988). Emotion/cognition interaction in personality development: A discrete emotions, functionalist analysis. *British Journal of Social Psychology*, *27*, 91–112.

Mascolo, M. F., & Fischer, K. W. (1998). The development of self through the coordination of component systems. In M. Ferrari & R. J. Sternberg (Eds.), *Self-awareness: Its nature and development*. New York: Guilford.

Maturana, H. R., & Varela, F. J. (1987). *The tree of knowledge: The biological roots of human understanding*. Boston: New Science Library.

Mesulam, M. (2002). The human frontal lobes: Transcending the default mode through contingent encoding. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 8–30). New York: Oxford University Press.

Moratti, S., Keil, A., & Stolarova, M. (2004). Motivated attention in emotional picture processing is reflected by activity modulation in cortical attention networks. *NeuroImage*, *21*, 954–964.

Nieuwenhuis, S., Yeung, N., Van den Wildenberg, W., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a Go/NoGo task: Effects of response conflict and trial-type frequency. *Cognitive, Affective & Behavioural Neuroscience*, *3*, 17–26.

Ochsner, K. N., Ray, R. D., Cooper, J. C., Robertson, E. R., Chopra, S., Gabrieli, J. D. E., et al. (2004). For better or for worse: Neural systems supporting the cognitive down- and up-regulation of negative emotion. *NeuroImage*, *23*, 483–499.

Panksepp, J. (1998). *Affective neuroscience: The foundations of human and animal emotions*. New York: Oxford University Press.

Pare, D., Collins, D. R., & Pelletier, J. G. (2002). Amygdala oscillations and the consolidation of emotional memories. *Trends in Cognitive Sciences*, *6*, 306–314.

Paus, T. (2001). Primate anterior cingulate cortex: Where motor control, drive and cognition interface. *Nature Reviews Neuroscience*, *2*, 417–424.

Paus, T. (2005). Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences*, *9*, 60–68.

Petrides, M., & Pandya, D. N. (2002). Association pathways of the prefrontal cortex and functional observations. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 31–50). New York: Oxford University Press.

Petrovic, P., Kalso, E., Petersson, K. M., & Martin, I. (2002). Placebo and opioid analgesia: Imaging a shared neuronal network. *Science*, *295*, 1740–1757.

Pezawas, L., Meyer-Lindenberg, A., Drabant, E. M., Verchinski, B. A., Munoz, K. E., Kolachana, B. S., et al. (2005). 5-HTTLPR polymorphism impacts human cingulate-amygdala interactions: A genetic susceptibility mechanism for depression. *Nature Neuroscience*, *8*, 828–834.

Poremba, A., & Gabriel, M. (1997). Amygdalar lesions block discriminative avoidance learning and cingulothalamic training-induced neuronal plasticity in rabbits. *Journal of Neuroscience*, *17*, 5237–5244.

Posner, M. I., & Rothbart, M. K. (2000). Developing mechanisms of self-regulation. *Development and Psychopathology*, *12*, 427–441.

Potegal, M., Hebert, M., DeCoster, M., & Meyerhoff, J. (1996). Brief, high frequency stimulation of the corticomedial amygdala induces a delayed and prolonged increase of aggressiveness in male Syrian golden hampsters. *Behavioural Neuroscience*, *110*, 1–12.

Prencipe, A., & Zelazo, P. D. (2005). Development of affective decision-making for self and other: Evidence for the integration of first- and third-person perspectives. *Psychological Science*, *16*, 501–505.

Price, J. L. (1999). Networks within the orbital and medial prefrontal cortex. *Neurocase*, *5*, 231–241.

Rolls, E. T. (1999). *The brain and emotion*. Oxford: Oxford University Press.

Rubia, K., Overmayer, S., Taylor, E., Williams, S. C. R., Simmons, A., Andrew, C., et al. (2000). Functional frontalisation with age: Mapping neurodevelopmental trajectories with fMRI. *Neuroscience and Biobehavioural Reviews*, *24*, 13–19.

Saarnat, H. B., & Netsky, M. G. (1974). *Evolution of the nervous system*. New York: Oxford University Press.

Spear, L. P. (2000). The adolescent brain and age-related behavioral manifestations. *Neuroscience and Biobehavioral Reviews*, *24*, 417–463.

Spear, L. P. (2003). Neurodevelopment during adolescence. In D. Cicchetti & E. F. Walker (Eds.), *Neurodevelopmental mechanisms in psychopathology* (pp. 62–83). Cambridge, UK: Cambridge University Press.

Stratford, T. R., & Kelley, A. E. (1999). Evidence of a functional relationship between the nucleus accumbens shell and lateral hypothalamus subserving the control of feeding behaviour. *Journal of Neuroscience*, *19*, 11040–11048.

Surguladze, S. A., Brammer, M. J., Young, A. W., Andrew, C., Travis, M. J., Williams, S. C., et al. (2003). A preferential increase in the extrastriate response to signals of danger. *Neuroimage*, *19*, 1317–1328.

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*, 201–216.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press/Bradford.

Thelen, E., & Smith, L. B. (1998). Dynamic systems theories. In W. Damon & R. M. Lerner (Eds.), *Handbook of child psychology: Volume 1: Theoretical models of human development* (5th ed., 935, pp. 563–634). Hoboken, NJ: John Wiley & Sons.

Thompson, C., Barresi, J., & Moore, C. (1997). The development of future-oriented prudence and altruism in preschoolers. *Cognitive Development*, *12*, 199–212.

Todd, R. M., Lewis, M. D., Meusel, L.-A., & Zelazo, P. D. (under review). The time course of emotion processing in early childhood: ERP responses to affective stimuli in a go-nogo task.

Tucker, D. M. (1992). Developing emotions and cortical networks. In M. R. Gunnar & C. Nelson (Eds.), *Minnesota symposia on child psychology: Vol. 24. Developmental behavioural neuroscience* (pp. 75–128). Hillsdale, NJ: Erlbaum.

Tucker, D. M. (2001). Motivated anatomy: A core-and-shell model of corticolimbic architecture. In G. Gainotti (Ed.), *Handbook of neuropsychology: Vol. 5. Emotional behaviour and its disorders* (2nd ed., pp. 125–160). Amsterdam, Netherlands: Elsevier.

Tucker, D. M., Derryberry, D., & Luu, P. (2000). Anatomy and physiology of human emotion: Vertical integration of brainstem, limbic, and cortical systems. In J. C. Borod (Ed.), *Handbook of the neuropsychology of emotion* (pp. 56–79). New York: Oxford University Press.

Tucker, D. M., Luu, P., Desmond, R. E., Jr., Hartry-Speiser, A., Davey, C., & Flaisch, T. (2003). Corticolimbic mechanisms in emotional decisions. *Emotion*, *3*, 127–149.

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

Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind: Cognitive science and human experience*. Cambridge, MA: MIT Press.

Zelazo, P. D., & Cunningham, W. A. (2007). Executive function: Mechanisms underlying emotion regulation. In J. Gross (Ed.), *Handbook of emotion regulation*. New York: Guilford.

Zelazo, P. D., & Mueller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.), *Handbook of childhood cognitive development*. Oxford: Blackwell.