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Executive Function: Mechanisms Underlying Emotion Regulation

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Abstract

Research on executive function (EF) is directed at understanding the conscious control of thought and action. Although EF can be understood as a domain-general construct at the most abstract functional level of analysis (i.e., as conscious goal-directed problem solving), more precise characterizations distinguish between the relatively “hot” motivationally significant aspects of EF and the more disinterested “cool” aspects (Zelazo & Müller, 2002). In this chapter, we propose a model of emotional regulation (ER) based on principles of EF (both “hot” and “cool”) that spans Marr’s (1982) three levels of analysis—computational (concerning what EF accomplishes), algorithmic (dealing in more detail with the way information is represented and how it is processed), and implementational (examining how the information processing is realized in the brain). This model highlights the roles of reflection (levels of consciousness) and rule use in the regulation of emotion, and makes initial steps toward explaining how these processes contribute to the subjective experience of complex emotions. Presentation of this model is intended to serve as a concise summary of research on EF and as an exploration of its implications for emotion regulation.

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Defining Emotion and Emotion Regulation

In agreement with a growing number of researchers (e.g., Barrett, Ochsner, & Gross, in press; Damasio, 1994), we suggest that a stark distinction between cognition and emotion reflects an outmoded adherence to a fundamentally moralistic worldview (reason is angelic, passion beastly). Instead, we suggest that emotion corresponds to an aspect of cognition—its motivational aspect. On this view, it is possible to have cognition that is more or less emotional, more or less motivated. Thus, we use the term *emotion* to refer to an aspect of human information processing that manifests itself in multiple dimensions: subjective experience, observable behavior, and physiological activity, among them. *Emotion regulation (ER)* refers to the modulation of motivated cognition and its many manifestations. ER can occur in a variety of ways (Gross & Thompson, this volume), but one of the most obvious varieties is the deliberate self-regulation of emotion via conscious cognitive processing, and it is this variety of ER that we will address in terms of EF. It is important to note that although we focus on the aspects of ER that are directly associated with processes of EF, we are not suggesting that this is the only route to ER (cf. Fitzsimons & Bargh, 2004). As with any complex psychological phenomenon, ER may well occur in a variety of ways (some of which may be quite automatic).

Executive Function

EF is generally recognized as an important but ill-understood umbrella term for a diverse set of "higher cognitive processes," including (but not limited to) planning, working memory, set shifting, error detection and correction, and the inhibitory control of prepotent responses (e.g., Roberts, Robbins, & Weiskrantz, 1998; Stuss & Benson, 1984; Tranel, Anderson, & Benton, 1994). These processes are recruited for the deliberate self-regulation of emotion, and in this chapter, we will attempt to explain how. First, however, we need to provide a characterization of EF. In what follows, we will describe EF at each of Marr's (1982) three levels of analysis—computational (concerning what EF accomplishes), algorithmic (dealing in more detail with the way information is represented and how it is processed), and implementational (examining how the information processing is realized in the brain)—and then show in more detail how EF plays a role in ER. A new model is outlined that relies on a distinction between hot and cool EF (see below), both of which are hypothesized to be involved in ER. This model highlights what we take to be the most important aspects of EF to be considered when seeking to understand ER.

Computational level. One way to capture the diversity of the processes associated with EF without simply listing them and without hypostasizing homuncular abilities (e.g., a Central Executive [Baddeley, 1996], or a Supervisory Attentional System [Norman & Shallice, 1986]) is to treat EF as a complex hierarchical function (Zelazo, Carter, Reznick, & Frye, 1997). In this view, which has its origins in the work of Luria (e.g., 1966) and Goldberg (e.g., Goldberg & Bilder, 1987), the function of EF is seen to be deliberate, goal-directed problem solving, and functionally distinct phases of problem solving can then be flexibly and dynamically organized around this function. Figure 1 illustrates how different aspects of EF contribute to the eventual outcome, as well as how EF unfolds as an iterative, essentially cybernetic (Weiner, 1948), process. Although this functional characterization does not, by itself, provide an adequate explanation of EF, it provides a framework within which one can understand the hierarchical structure of EF and consider the way in which more basic cognitive processes (e.g., working memory) contribute to particular aspects of EF (e.g., the role of working memory in intending).

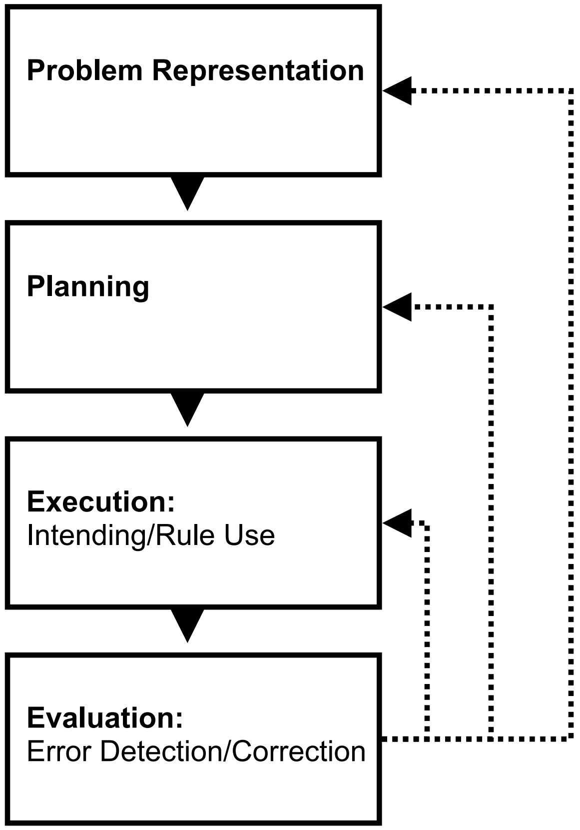

Figure 1. A problem-solving framework for understanding temporally and functionally distinct phases of executive function, considered as a functional construct. Dashed lines indicate optional recursive feedback loops. (Adapted with permission from P. D. Zelazo, A. S. Carter, J. S. Reznick, & D. Frye [1997]. Early development of executive function: A problem solving approach. *Review of General Psychology, 1*, 198-226).

To appreciate the utility of this abstract, functional characterization, consider how it applies to the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948), which is widely regarded as "the prototypical EF task in neuropsychology" (Pennington & Ozonoff, 1996, p. 55). In the WCST, participants are presented with four target cards that differ on three dimensions (number, color, and shape), and asked to sort a series of test cards that match different target cards on different dimensions. Participants must discover the sorting rule by trial and error, and after a certain number of consecutive correct responses, the sorting rule is changed. The WCST taps numerous aspects of EF, and, as a result, the origin of errors on this task is difficult to determine (but see Barceló & Knight, 2002; Delis, Squire, Bihrle, & Massman, 1992, for efforts to distinguish between different types of error). To perform correctly, one must first construct a representation of the problem space, which includes (a) one's current state, (b) one's goal state, and (c) options for reducing the discrepancy between (a) and (b). In the WCST, a key part of the problem consists in identifying the relevant dimensions. After representing the problem, one must choose a promising plan—for example, sorting according to shape. After selecting a plan, one must (a) keep the plan in mind long enough for it to guide one's thought or action, and (b) actually carry out the prescribed behavior. Keeping a plan in mind to control behavior is referred to as *intending*; translating a plan into action is *rule use*. Finally, after acting, one must evaluate the consequences of this action to determine whether one's goal state has been attained. This phase includes both error detection and, if necessary, error correction. Error correction entails revisiting earlier phases in the sequences, thereby initiating another iteration of the sequence—either in whole or in part. Failures of EF can occur at each problem-solving phase, so there are several possible explanations of poor performance on the WCST. For example, perseveration could occur after a rule change in the WCST either because a new plan was not formed or because the plan was formed but not carried out.

Notice that in this example, as in many situations, one needs to consider multiple goals simultaneously, at various levels of abstraction (Carver & Sheier, 1982). For example, one needs to pursue the relatively proximal subgoal of executing one's plan—sorting by shape—in the service of fulfilling the more distal, but still explicit, goal of performing well on the WCST. Thus, EF needs to be understood as a complex, hierarchical function at this level of analysis.

This computational characterization of EF also applies to situations involving ER. Consider, for example, a child who is hit accidentally by another child on a playground. Does the first child hit back, or does he diffuse the situation as he has been told to do by his teacher? The answer may depend on whether ER is successful, and ER may fail at any of the problem solving phases. (1) The child may fail to represent the problem adequately. For example, he may be biased to represent such situations as threatening, and he may have difficulty flexibly reinterpreting the situation. (2) Alternatively or additionally, he may fail to plan or think ahead properly. For example, he may fail to anticipate the negative consequences of responding aggressively. (3) He may understand the rules that govern the situation (e.g., 'I should not hit others' or 'I should do as I am asked by my teacher') but fail to use these rules, just as people fail to use rules that they know on tests of rule use (e.g., Zelazo, Frye, & Rapus, 1996; Zelazo et al., 2003). (4) Finally, he may have difficulty learning from past experience.

The algorithmic level. Research on EF has generated numerous proposals regarding the cognitive processes that help fulfil the higher-order function of EF. These processes include metacognition, selective attention, working memory, inhibitory control, and rule use, as well as combinations of these processes (e.g., see chapters in Roberts et al., 1998; Stuss & Knight, 2002). One approach that serves to integrate these processes has been motivated by research on the development of EF in childhood and across the lifespan. According to the Levels of Consciousness Model (e.g., Zelazo, 2004), EF (as defined here) is accomplished, in large part, by the ability to formulate, maintain in working memory, and then act on the basis of rule systems at different levels of complexity—from a single rule relating a stimulus to a response, to a pair of rules, to a hierarchical system of rules that allows one to select among incompatible pairs of rules. In this account, rules are formulated in an ad hoc fashion in potentially silent self-directed speech. These rules link antecedent conditions to consequences, as when we tell ourselves, "If I see a mailbox, then I need to mail this letter." When people reflect on the rules they represent, they are able to consider them in contradistinction to other rules and embed them under higher order rules, in the same way that we might say, "If it's before 5 p.m., then if I see a mailbox with a late pick-up, then I need to mail this letter, otherwise, I'll have find a mailbox with an early morning pick-up." In this example, a simple conditional statement regarding the mailbox is made dependent on the satisfaction of yet another condition (namely, the time). More complex rule systems permit the more flexible selection of certain rules for acting when multiple conflicting rules are possible. This, in turn, changes the content of one's action-oriented representations (held in working memory), resulting in the amplification and diminution of attention to potential influences on thought (inferences) and action.

Increases in rule complexity are made possible by corresponding increases in the extent that one reflects on one's representations. Rather than taking rules for granted and simply assessing whether their antecedent conditions are satisfied, reflection involves making the rules themselves an object of consideration and considering them in contradistinction to other rules at that same level of complexity. Reflection, on this account, is taken to involve the recursive reprocessing of information. Each degree of recursion results in a new "level of consciousness," and each level of consciousness allows for the integration of more information into an experience before it is replaced by new intero- or exteroceptor stimulation. Moreover, each level of consciousness allows for the formulation and use of more complex rule systems. So, we might contrast relatively automatic action at a lower level of consciousness with relatively deliberate action at a higher level of consciousness. The former type of action is performed in response to the most salient, low-resolution aspects of a situation, and it is based on the formulation of a relatively simple rule system—likely a rule describing a stereotypical response to the situation. The more deliberate action occurs in response to a more carefully considered construal of the same situation, and it is based on the formulation of a more complex, and more flexible system of rules or inferences. As a general rule, reflection is engaged as needed in the service of problem solving goals, and in the flexible, iterative way described earlier in our treatment of EF at the computational level of analysis. Details of this model (showing, for example, the cognitive implications of each level of consciousness) are presented elsewhere (e.g., Zelazo, 2004; Zelazo, Gao, & Todd, in press).

The tree diagram in Figure 2 illustrates the way in which hierarchies of rules can be formed through reflection—the way in which one rule can first become an object of explicit consideration at a higher level of consciousness, and then be embedded under another higher order rule and controlled by it. Rule A, which indicates that response 1 (r_1) should follow stimulus 1 (s_1), is incompatible with rule C, which connects s_1 to r_2. Rule A is embedded under, and controlled by, a higher order rule (rule E) that can be used to select rule A or rule B, and this, in turn, is embedded under a still higher order rule (rule F) that can be used to select the discrimination between rules A and B as opposed to the discrimination between rules C and D. This higher order rule makes reference to setting conditions or contexts (c_1 and c_2) that condition the selection of lower order rules, and that would be taken for granted in the absence of reflection. Higher-order rules of this type (F) are required in order to use *bivalent* rules in which the same stimulus is linked to different responses (e.g., rules A and C). Simpler rules like E suffice to select between *univalent* stimulus-response associations—rules in which each stimulus is associated with a different response.

Consider, for example, the goal of getting a letter into the mail as soon as possible. Rule A may specify that you should deposit your envelope in the first mailbox you see that has a late (e.g., 5 pm) pick-up time. Rule B may indicate that you should refrain from depositing your envelope in mailboxes that only have early morning pick-ups. Reflecting on rules A and B allows you to use rule E to discriminate between mailboxes that will help or hinder you in pursuit of your goal; A signifies approach, B avoidance. If, however, it is after 5 pm, then you need to deposit your envelope in a mailbox with an early morning pick-up and avoid mailboxes that only have late pick-ups. The time, therefore, is a context that needs to be considered. Reflection on this fact calls for formulation of another rule, rule F, for selecting between one context, *before 5 pm*, and another, *after 5 pm*. If it is after 5 pm, you will want to avoid depositing your envelope in mailboxes with a 5 pm pick-up (observing rule C instead of rule A) and proceed with another new rule, rule D: Deposit the envelope in a mailbox with an early morning pick-up.

Notice that in order to formulate a higher order rule such as F and deliberate between rules C and D, on the one hand, and rules A and B, on the other, one has to be aware of the fact that one knows both pairs of lower order rules. Figuratively speaking, one has to view the two rule pairs from the perspective of (F). This shows how increases in reflection on lower order rules are required for increases in embedding to occur. Each level of consciousness allows for the formulation and maintenance in working memory of a more complex rule system. A particular level of consciousness is required to use a single rule such as (A); a higher level of consciousness is required to select between two univalent rules using a rule such as (E); a still higher level is required to switch between two bivalent rules using a rule such as (F).

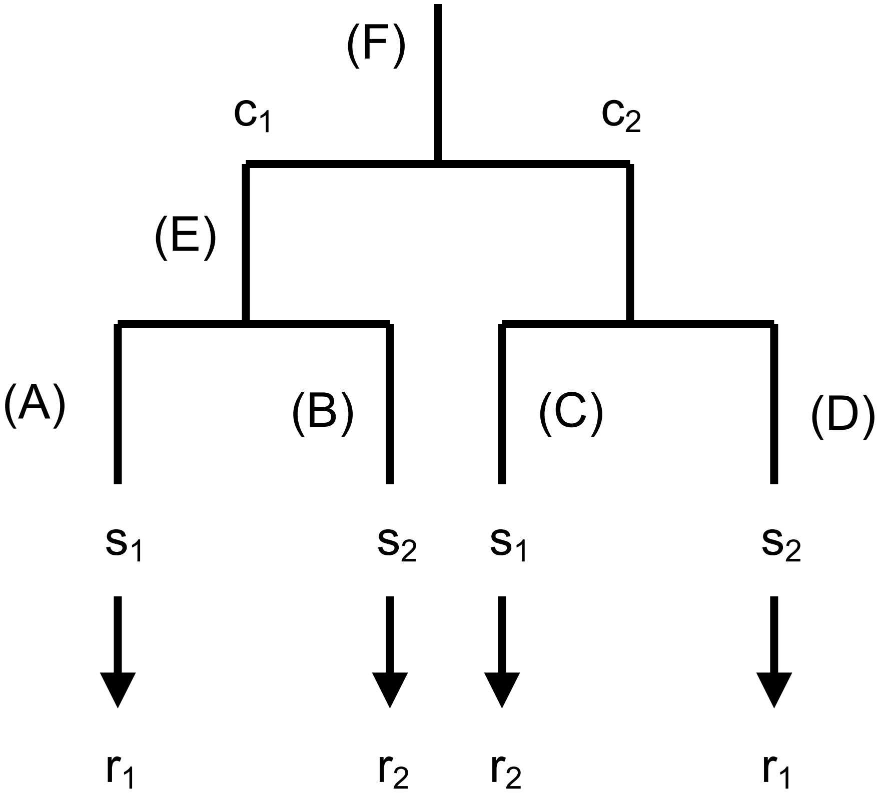

Figure 2. Hierarchical tree structure depicting formal relations among rules (adapted from Frye, D., Zelazo, P. D., & Palfai, T. (1995). Theory of mind and rule-based reasoning. *Cognitive Development, 10*, 483-527). Note: c_1 and c_2 = contexts; s_1 and s_2 = stimuli; r_1 and r_2 = responses.

The implementational level. The Levels of Consciousness Model (e.g., Zelazo, 2004) is a process model that describes the steps leading from the representation of a stimulus to the execution of a controlled response. In this model, reflection and rule use, which requires the maintenance of information in working memory, are the primary psychological processes involved in fulfilling the relatively abstract function of deliberate goal-directed problem solving (i.e., EF). The implementional level concerns how these psychological processes are realized in the brain. Considerable research remains to be conducted at this level of analysis, but there is now strong evidence that EF depends importantly on the integrity of neural systems involving PFC (e.g., Luria, 1966; Miller, 2000; Stuss & Benson, 1986), although it is also clear that other brain regions are involved, and that different regions of PFC are especially important for particular aspects of EF (e.g., Bunge, 2004). A great deal of current research in cognitive neuroscience is directed at identifying specific structure-function relations in regions of PFC (e.g., Stuss & Knight, 2002).

Bunge and Zelazo (in press) summarized a growing body of evidence that PFC plays a key role in rule use, and that different regions of PFC are involved in representing rules at different levels of complexity—from a single rule for responding when stimulus-reward associations need to be reversed (orbitofrontal cortex; OFC; Brodmann's area

[BA] 11[1]), to sets of conditional rules (ventrolateral prefrontal cortex [VL-PFC; BA 44, 45, 47] and dorsolateral prefrontal cortex [DL-PFC; BA 9, 46]), to explicit consideration of task sets (frontopolar cortex or rostrolateral prefrontal cortex [RL-PFC; BA 10]; see Figure 4). The role of OFC in rule use can be seen in object reversal, when one learns a simple discrimination between two objects and then the discrimination is reversed (the previously unrewarded object is rewarded and vice versa). To respond flexibly and rapidly on this task, it helps to represent the new stimulus-reward association explicitly, as a simple stimulus-reward rule maintained in working memory (Schoenbaum & Setlow, 2001); damage to OFC leads to perseverative responding in both human adults (Rolls, Hornak, Wade, & McGrath, 1994) and non-human primates (Dias, Robbins, & Roberts, 1996). In the absence of a simple stimulus-reward association maintained in working memory, one is likely to respond to the most salient association that one has to the situation—one is likely to respond to the previously rewarded stimulus.

In contrast to OFC, both VL-PFC and DL-PFC have been consistently implicated in the retrieval, maintenance, and use of more complex sets of conditional stimulus-response rules—in lesion studies and fMRI studies (e.g., Wallis & Miller, 2003; see Bunge, 2004, for review). For example, using fMRI, Crone, Wendelken, Donohue, and Bunge (2006) found that both VL-PFC and DL-PFC are active during the maintenance of sets of conditional rules, and that they are sensitive to rule complexity, showing more activation for bivalent rules than for univalent rules. Bunge, Kahn, Wallis, Miller, and Wagner (2003) observed that these two regions are also more active for more abstract conditional rules (‘match’ or ‘non-match’ rules, whereby different actions are required depending on whether two objects match or not) than for specific stimulus-response associations. However, fMRI data suggest that DL-PFC may be especially important when participants must switch from one bivalent rule to another, and hence suppress the previously relevant rule (Crone et al., 2006). That is, whereas VL-PFC may be necessary for representing pairs of conditional rules, DL-PFC may be recruited when representing bivalent rules that place heavy demands on attentional selection (Miller, 1999) or response selection (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). These rules may be quite general in their application, extending, for example, to the selection among competing cues in semantic memory (Thompson-Shill, D’Esposito, Aguirre, & Farah, 1997). In effect, VL-PFC together with DL-PFC may serve to foreground some pieces of information while backgrounding others, all in the service of a goal.

Finally, fMRI studies suggest that RL-PFC plays an important role in the temporary consideration of higher-order rules (such as E and F in Figure 3) for selecting among task sets, as when switching between two abstract rules (Bunge, Wallis, Parker, et al., 2005; Crone et al., 2006), integrating information in the context of relational reasoning (Christoff et al., 2001), or coordinating hierarchically embedded goals (Koechlin, Basso, Pietrini, Panser, & Grafman, 1999). This region may be involved in reflecting on lower-order rules and selecting among them at any level within a rule hierarchy—selecting between two univalent rules or switching between two pairs of bivalent rules. As a result, RL-PFC may interact with different parts of prefrontal cortex (i.e., VL-PFC or DL-PFC) depending on the type of task involved (Sakai & Passingham,

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[1] For the purposes of this chapter, we consider OFC to be primarily the medial aspects of the orbital frontal cortex.

2003, 2006)—and hence, we would argue, depending on the complexity of the rule systems involved.

Figure 3 illustrates the way in which regions of PFC may correspond to rule use at different levels of complexity. As should be clear, the function of PFC is proposed to be hierarchical in a way that corresponds to the hierarchical complexity of the rule use underlying EF. As individuals engage in reflective processing, ascend through levels of consciousness, and formulate more complex rule systems, they recruit an increasingly complex hierarchical network of PFC regions.

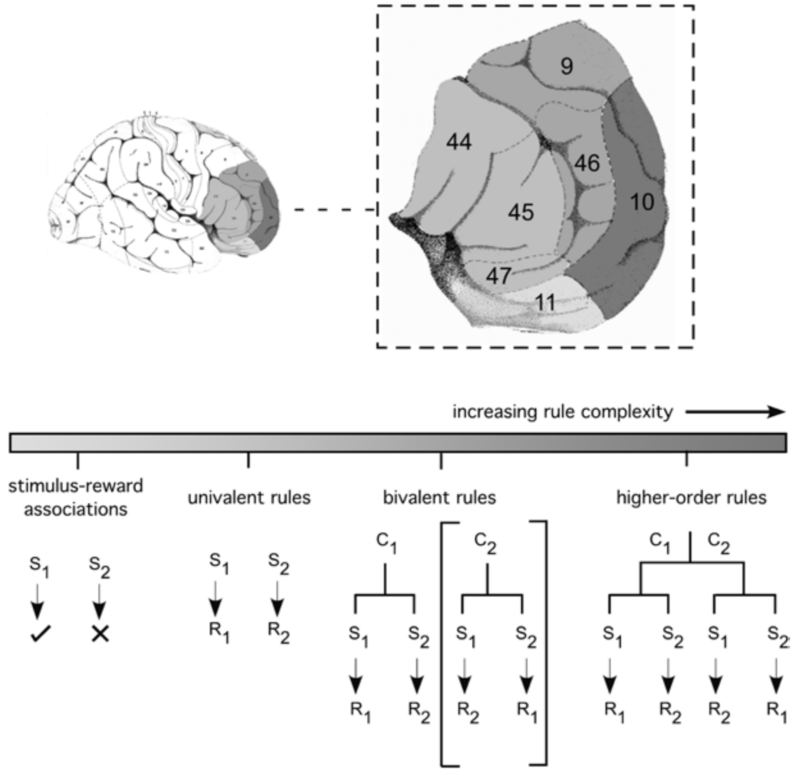

Figure 3. A hierarchical model of rule representation in PFC. A lateral view of the human brain is depicted at the top of the figure, with regions of PFC identified by the Brodmann areas (BA) that comprise them: Orbitofrontal cortex (BA 11), ventrolateral PFC (BA 44, 45, 47), dorsolateral PFC (BA 9, 46), and rostrolateral PFC (BA 10). The PFC regions are shown in various shades of gray, indicating which types of rules they represent. Rule structures are depicted below, with darker shades of gray indicating increasing levels of rule complexity. The formulation and maintenance in working memory of more complex rules depends on the reprocessing of information through a series of levels of consciousness, which in turn depends on the recruitment of additional regions of PFC into an increasingly complex hierarchy of PFC activation. Note: S = stimulus; check = reward; cross = nonreward; R = response; C = context, or task set. Brackets indicate a bivalent rule that is currently being ignored. (Reprinted with permission from Bunge, S., & Zelazo, P. D. (in press). A brain-based account of the development of rule use in childhood. *Current Directions in Psychological Science*.).

One important implication of this conceptualization of EF is that it emerges from a dynamic interaction between bottom-up and top-down processes. As a result, EF takes time to occur. Information must first be processed at lower levels of consciousness and in particular parts of PFC before it can be passed forward and processed at higher levels of consciousness and in other parts of PFC. Additionally, information about a stimulus is reprocessed iteratively using the same network that was used for the original processing, with higher levels of consciousness guiding the reprocessing of information at lower levels of consciousness. Specifically, top-down PFC processes foreground specific aspects of information (hence backgrounding others), and these re-weighted representations are used to "reseed" initial EF processing by influencing ongoing processing of the stimulus.

Because reflective processing takes time, the model makes predictions about the time course of EF as well as the potential consequences of requiring rapid responses (cf. White, 1965). EF can only be as effective as the amount of time allowed to complete the process. Many times, one must reach a judgment or initiate a behavioral sequence before EF processes have reached an optimal solution. In these situations, one can have partial EF—despite a person's goals.

Hot vs. Cool EF: Towards a New Model of Emotion Regulation as EF

Although EF can be understood as a domain-general construct at the most abstract, functional level (i.e., as conscious goal-directed problem solving), more precise characterizations (at the algorithmic and implementational levels) necessitate another distinction—that between the relatively "hot" motivationally significant aspects of EF more associated with ventral parts of PFC, and the more motivationally independent "cool" aspects more associated with lateral PFC (Zelazo & Müller, 2002; cf. Metcalfe & Mischel, 1999; Miller & Cohen, 2001). Whereas cool EF is more likely to be elicited by relatively abstract, decontextualized problems (e.g., sorting by color, number, or shape in the WCST), both hot and cool EF are required for problems that involve the regulation of motivation. Thus, hot EF is especially prominent when people really *care* about the problems they are attempting to solve, although in fact, ER involves both hot EF (control processes centered on reward representations) and cool EF (higher order processing of more abstract information).

Interestingly, the link between EF and ER is most closely seen when the problem to be solved just is that of modulating emotion, as in ER. In fact, in such cases, EF *just is* ER—the two constructs are isomorphic. Yet, when the modulation of emotion occurs in the service of solving another problem (which we believe is the case for the majority of situations), then EF *involves* ER. It should be noted that ER in these two cases may differ. For example, when ER is a secondary goal, there may be a greater need for selecting among task sets (and hence, greater RL-PFC involvement). Although it seems likely that ER occurs most often in the service other goals, research on ER has generally relied on paradigms in which ER is the participants' primary objective (e.g., Ochsner, Ray, Robertson, et al., 2004).

This characterization of hot EF in contradistinction to cool EF is consistent with neuroanatomical evidence that ventral PFC differs from lateral PFC in their patterns of connectivity with other brain regions. OFC is part of a frontostriatal circuit that has strong connections to the amygdala and other parts of the limbic system. Consequently, OFC is anatomically well suited for the integration of affective and nonaffective information, and for the regulation of appetitive/motivated responses (e.g., Damasio, 1994; Rolls, 1999). In contrast, these connections are less direct in the case of lateral PFC (indeed, they are partly mediated by OFC). In addition to its connections with OFC, DL-PFC is connected to a variety of brain areas that would allow it to play an important role in the integration of sensory and mnemonic information and the regulation of intellectual function and action. These include: the thalamus, parts of the basal ganglia (the dorsal caudate nucleus), the hippocampus, and primary and secondary association areas of neocortex, including posterior temporal, parietal, and occipital areas (e.g., Fuster, 1989).

The distinction between hot and cool EF is also consistent with a large body of research regarding the functions of DL-PFC, on the one hand, and OFC, on the other. Traditionally, research on EF in human beings has focussed almost exclusively on DL-PFC, using measures such as the WCST and the Tower of London (Shallice, 1988). Results of this research contributed our current characterization of cool EF. A good deal of early research on OFC was conducted with non-human animals, using two relatively simple paradigms: object reversal learning and extinction. As noted earlier, in object reversal, animals learn a simple discrimination between two objects and then the discrimination is reversed (the previously unrewarded object is rewarded and vice versa). On this task, animals with lesions to (the inferior convexity of) OFC fail to switch their responses, and instead perseverate on the initial discrimination (e.g., Butter, 1969; Dias et al., 1996; Iversen & Mishkin, 1970; Jones & Mishkin, 1972). More recent research has demonstrated that human patients with acquired OFC damage also reveal deficits in reversal learning, including perseverative responding to the previously rewarded stimulus (Fellows & Farah, 2003; Rolls, Hornak, Wade, & McGrath, 1994).

Response extinction tasks are similar to reversal learning tasks in that they also involve a change in the reinforcement contingencies after a response has been learned to criterion. In this case, a response is reinforced, and then reinforcement is withheld. In such situations, non-human primates with lesions to (caudal) OFC (e.g., Butter, Mishkin, & Rosvold, 1963) and human patients with OFC damage (Rolls et al., 1994) display resistance to extinction, continuing to respond to the non-reinforced stimulus.

Findings of this sort have led to suggestions that OFC is heavily involved in the re-appraisal of the affective or motivational significance of stimuli (e.g., Rolls, 1999; Rolls, 2004). On this view, while the amygdala is primarily involved in the initial learning of stimulus-reward associations (e.g., Killcross, Robbins, & Everitt, 1997; LeDoux, 1996), reprocessing of these relations is the province of OFC. In terms of the Bunge and Zelazo (in press) model, reprocessing—as assessed by relatively simple tasks such as object reversal and extinction—may rely heavily on OFC because it requires the explicit representation of a simple stimulus-reward association to govern approach or avoidance of a concrete stimulus.

Recently, researchers have noted that human patients with OFC damage are often impaired at the self-regulation of social behaviour—especially in generating appropriate emotional reactions given social norms (Beer, Heerey, Keltner, Scabini, & Knight, 2003; Damasio, 1994; Rolls et al., 1994). Researchers working with human patients have also used a variety of more complex laboratory measures of hot EF, such as the Iowa Gambling Task (e.g, Bechara, A. Damasio, H. Damasio, & Anderson, 1994), which assesses decision-making about uncertain events that have emotionally significant consequences (i.e., meaningful rewards and/or losses). Although initial studies suggested that OFC alone (especially on the right) was important for performance on this task, more recent research has revealed an important role for DL-PFC (Fellows & Farah, 2005; Manes, Sahakian, Clark, Rogers, Antoun, Aitken, & Robbins, 2002; see also Hinson et al., 2002). This may be due to the complexity of the rules required.

In addition, however, it should be noted that the various regions of PFC are parts of a single coordinated system and probably work together—even in a single situation. Thus, it seems likely that decision making is routinely influenced in a bottom-up fashion by affective reactions (e.g., Damasio, 1994; Gray, 2004) and the representation of reward value (e.g., Rolls, 1999). Conversely, it seems likely that a successful approach to solving hot problems is to reconceptualize the problem in relatively neutral, decontextualized terms, and try to solve it using cool EF (cf. Mischel, Shoda, & Rodriguez, 1989)—reflecting on the situation, creating more complex rule systems, and recruiting more lateral regions of PFC.

Indeed, in terms of the hierarchical model of PFC function (Figure 3), it is not that ventral regions such as OFC are exclusively involved in hot EF, but rather that they remain more activated even as the hierarchy of PFC is elaborated. Simple rules for approach vs. or avoiding concrete stimuli (the provenance of OFC) are more difficult to ignore in motivationally significant situations, so in effect, hot EF involves increased bottom-up influences on PFC processing, with the result that hot EF (vs. cool executive function) requires relatively more attention to (and activation of) lower levels in rule hierarchies—discriminations at that level become more salient, leading to relatively more ventral PFC (i.e., OFC and perhaps VL-PFC) activation even when higher levels in the hierarchy are also involved. Rather than positing discrete systems for hot and cool EF, this model views hot-cool as a continuum that corresponds to the motivational significance of the problem to be solved, and to the degree of reflection and rule complexity made possible by the hierarchy of PFC function. These two dimensions (motivational significance and reflection or reprocessing) are understood to be correlated and to correspond to what has been called psychological distance from the situation (Carlson, David, & Leach, 2005; Dewey, 1931/1985; Sigel, 1993; Zelazo, 2004)—a cognitive separation from the exigencies of the situation. It should be noted, however, that it is also possible that rule complexity and motivational significance are orthogonal aspects of prefrontal organization: More anterior parts of PFC may represent more complex rules, and more ventral parts of PFC may represent reward-related information. Further research is needed to test these alternatives.

Finally, another distinction that becomes relevant when considering EF at the implementational level is that between left and right hemispheres of the brain (cf. Tucker & Williamson, 1984). A growing body of evidence suggests that right PFC may be more likely to be involved in hot EF than cool EF. For example, damage to right (or bilateral) OFC has a greater effect on social conduct, decision-making, emotional processing, and other purported OFC functions than does damage to left OFC (e.g., Manes et al., 2002; Rolls et al., 1994; Stuss, 1991; Stuss & Alexander, 1999; Stuss et al., 2001; Tranel, Bechara, & Denburg, 2002). As discussed by Bechara (2004; see also Tranel et al., 2002), patients with right OFC damage reveal marked impairments in everyday functioning as well as on the Iowa Gambling Task, and these effects are similar to those revealed in bilateral OFC patients. By contrast, patients with left OFC damage are relatively unimpaired, suggesting that the reliable impairments demonstrated by bilateral OFC patients may derive primarily from right OFC.

There are several possible reasons why right OFC may be so important for these functions. Bechara (2004) suggests that right-left hemispheric asymmetries in OFC function may derive from the differential involvement of the right and left hemispheres in avoidance (negative affect) and approach (positive affect), respectively (see also Davidson & Irwin, 1999; Davidson, Jackson, & Kalin, 2000). That is, adaptive decision-making on the Iowa Gambling Task, and possibly measures of affective decision making more generally, requires avoidance of seemingly positive responses (a function for which right OFC may be particularly well suited). The right hemisphere has also been implicated in the mapping of bodily states and the comprehension of somatic information (Davidson & Schwartz, 1976), and this too may help to explain the relative importance of right OFC to everyday decision-making (Bechara, 2004; Damasio, 1994).

The hemispheric asymmetry in approach and avoidance is relevant in its own right. Building on earlier work using baseline resting EEG, research has revealed considerable evidence that processing negative information is more associated with activation in regions of right PFC (Anderson, Christoff, Stappen, et al. 2003; Cunningham, Johnson, Gatenby et al., 2003; Cunningham, Raye, & Johnson, 2004; Sutton et al., 1997), whereas processing positive information is more associated with activation in regions of left PFC (Anderson et al., 2003; Cunningham et al., 2004; Nitschke, Nelson, Rusch, Fox, Oakes, & Davidson, 2003; Kringelbach, O'Doherty, Rolls, & Andrew, 2003; see Wager, Phan, Liberzon, & Taylor, 2003, for a meta-analysis). Given that human beings appear biased to attend to negative vs. positive information (Ito, Larsen, Smith, et al., 1998), and that negative information is generally more arousing (Ito, Cacioppo, & Lang, 1998), it may be the case that right OFC is more involved in processing information with motivational significance, rather than negative information per se.

Summary. In the first part of this chapter, we suggested that EF can be understood at each of Marr's (1982) 3 levels of analysis—computational, algorithmic, and implementational. At the computational level, we characterized EF as an abstract, hierarchical, iterative, cybernetic function: deliberate, goal-directed problem solving. At the algorithmic level, we outlined a process model of EF that emphasizes the roles of reflection (through a series of levels of consciousness) and the formulation, maintenance in working memory, and execution of rule systems that vary in hierarchical complexity. At the implementation level, we presented a hierarchical model of PFC function. Key properties at the computational level—EF as hierarchical, iterative, and cybernetic—also apply to the algorithmic and implementational levels because these levels fulfil the function specified at the computational level.

We then distinguished between hot and cool aspects of EF and suggested that hot EF is associated with higher degrees of motivational significance. At the algorithmic level, this corresponds to attention to relatively simple discriminations between approaching and avoiding stimuli that are construed as relatively concrete. At the implementational level, this corresponds to greater activation in ventral PFC and greater right hemisphere involvement.

This distinction is the basis of a new model of ER, which we now explore in more detail—again in terms of Marr's (1982) levels.

A New Model of ER

Computational level. At the computational level, one may have as a primary or secondary goal, the modulation of emotion. Modulation may involve emotional upregulation (increasing the intensity of a specific emotion), emotional downregulation (decreasing the intensity of a specific emotion), maintaining an emotion, or a qualitative change in one's emotional reactions. Consider the case of downregulating anger, as a primary goal. First, one has to represent the problem, assessing (a) one's current state—a high level of anger, (b) one's goal state—a reduction in anger and, correlatively, an increase in detachment, and (c) options for reducing the discrepancy between (a) and (b). These options may include reappraisal of the anger-provoking stimulus, simple distraction, or reminding oneself about the extent to which one values detachment, among other possibilities. Second, one has to select a promising plan from among these options, considering the relative efficacy of the options as well as the effort involved. Given that one has other pressing demands, such as an article to write, distraction may be likely to work and easy to implement, so one proceeds to the third general step of executing this plan. Now, one needs to adopt a goal of focusing one's attention on the article, and one needs to keep this goal in mind and act on the basis of it despite a tendency to dwell on the anger-provoking stimulus. When absorbed in writing the article, all is well; however, when one's attention reverts to the stimulus, one has to recognize that one's efforts at downregulation have failed. That is, one has to engage in evaluation, including taking steps to correct one's errors—for example, by stepping up one's efforts to attend to a relatively engaging aspect of the distracting activity.

In most cases, one needs to consider multiple goals simultaneously, at various levels of abstraction, and one pursues them more or less automatically (Bargh, 1989; Carver & Sheier, 1982; Shallice, 1988). EF is involved in just those cases where one is considering goals consciously and one is deliberately attempting to obtain them; normally one pursues a limited number of such goals at the same time. Nonetheless, as we saw, EF needs to be understood as a complex hierarchical function, and one inevitably needs to pursue more proximal subgoals (e.g., executing a plan) in the service of fulfilling a more distal, but still explicit, goal (e.g., solving the problem). It seems likely that emotion regulation is often a subgoal pursued in the service of another goal. That is, one strives to regulate one's emotion (e.g., upregulation or downregulation) *in order* to foster the fulfillment of some other goal about which one cares.

Algorithmic level. At the algorithmic level, ER involves reflection and the formulation and use of rules at various levels of complexity. Reflection and rule use allow one to progress through the functional phases identified at the computational level of analysis. Whether ER is the primary goal of EF or a subgoal, it will involve the elaboration (via the reprocessing of information through levels of consciousness) of an increasingly complex rule system, or system of inferences. This more complex rule system, maintained in working memory as the activated contents of consciousness, entails a reappraisal of the emotion-relevant situation. That is, it entails contextualization of the situation; rather than accepting a relatively superficial gloss of the situation—one that extracts only its most salient, low-resolution aspects, leading to a relatively simple approach-avoidance discrimination—one's representation of the situation is reprocessed and integrated with other information about contexts in which the situation may be understood. One consequence of the ascent through levels of consciousness will be an increase in psychological distance (e.g., Dewey, 1931/1985) from the situation, which is bound to result in cooler EF. Another consequence of the more carefully considered construal of the situation, based on the formulation of a more complex system of rules, is that one can now follow higher order rules for selecting certain aspects of the situation to which to attend. Generally speaking, attending selectively to certain aspects of the now broadly construed situation will be an effective way to modulate one's emotional reactions to the situation. For example, one may increase the intensity of one's emotional reaction by attending to more provocative aspects, or decrease the intensity of one's reaction by focussing on less provocative aspects. In contrast, processing that is restricted to a relatively low level of consciousness is likely to be perseverative, and this type of processing may underlie rumination in some cases.

Implementational level. In addition to the hierarchically arranged regions of lateral PFC depicted in Figure 3, ER involves a number of other neural structures, and it is instructive to show how these regions may interact with PFC. Indeed, attempting to understand ER in terms of EF, and hence considering the interplay between top-down and bottom-up processes that occurs in ER, prompts us to develop a more comprehensive neural model of ER, albeit one that is still focused relatively exclusively on PFC (e.g., ignoring the key roles of parietal cortex and the hippocampus) and that glosses over important distinctions within regions (e.g., within the limbic circuit: nucleus accumbens, ventral striatum, and nuclei of the amygdalae, etc.; LeBar & LeDoux, 2003).

The implementational level of our model of EF is depicted as a circuit diagram in Figure 4. To describe the model at this level, we first follow the flow of information involved generating an emotional reaction and triggering some efforts at ER. Perceptual information about a stimulus is processed via the thalamus and fed forward (via the direct, subcortical route) to the amygdala, which generates an initial, unreflective motivational tendency to approach or avoid the stimulus (e.g., LeDoux, 1996). This amygdala response leads to various emotional sequelae not depicted here (e.g., sympathetic activation), but it also serves as input to OFC, which implements an initial, relatively simple level of ER by processing amygdala output relative to a learned context (and simple approach-avoidance rules). When OFC activation fails to suffice to generate an unambiguous response to the stimulus (e.g., because the stimulus is ambivalent or signals the presence of an error), this triggers activation in the anterior cingulate cortex (ACC), which responds to the motivational significance of the stimulus—as understood at this level of processing. ACC, on this model, serves to initiate the reprocessing of information via VL-PFC and then DL-PFC, with RL-PFC playing a key, transient role in the explicit consideration of task sets. Broca's area is depicted separately from VL-PFC in Figure 4 in order to capture the fact that the rule use involved in these top-down regulatory processes may be intrinsically linguistic (i.e., it may be mediated by private speech; Vygotsky, 1962; Luria, 1961). At the same time, however, we note that self-directed speech may not be necessary in some cases, consistent with research on the emotional regulation of prejudice showing that right PFC, and not left PFC, is sometimes involved in regulation (Cunningham, Johnson, et al., 2004; Richeson et al., 2004).

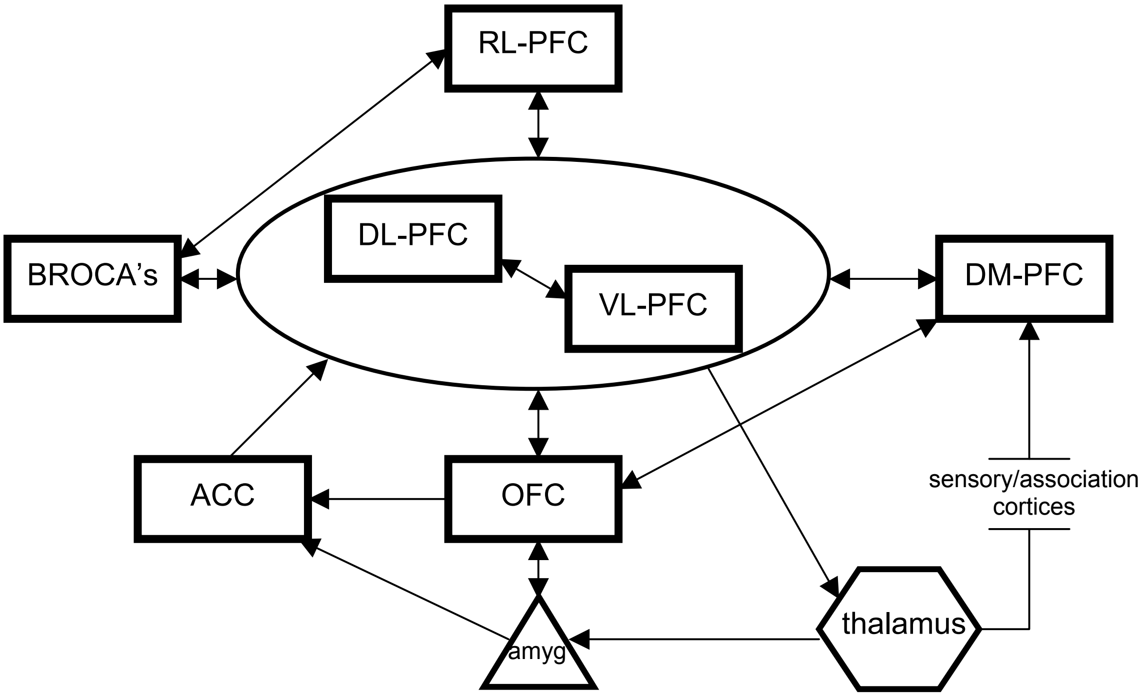

Figure 4. Neural circuitry underlying ER. Information about a sensory stimulus is processed by the thalamus and projected to the amygdala, leading to an initial motivational tendency to approach or avoid the stimulus, but also initiating further processing of the stimulus by the anterior cingulate cortex (ACC) and orbitofrontal cortex (OFC). ACC responds to the motivational significance of the situation and may serve to recruit additional reprocessing of the stimulus via ventrolateral prefrontal cortex (VL-PFC) and then dorsolateral prefrontal cortex (DL-PFC), with rostrolateral prefrontal cortex (RL-PFC) playing a transient role in the explicit consideration of task sets. Broca's area is involved insofar as top-down regulatory processes rely on private speech, and it is depicted separately from VL-PFC, of which it is a part. Reprocessing by lateral regions of PFC corresponds to reflection (through levels of consciousness) and the elaboration of rule hierarchies, and it serves to regulate emotion by amplifying or suppressing attention to certain aspects of the situation (thalamic route) and by biasing simple approach-avoidance rules in OFC.

As in EF more generally, in ER different regions of lateral PFC are recruited as one engages in reflection and in the retrieval, maintenance, and use of rule systems at different levels of complexity. This route to ER is tantamount to the initiation of elaborative processing of a motivationally significant stimulus; as mentioned at the algorithmic level, this entails contextualization of the situation, and it may result in ER via reciprocal suppression between levels in the hierarchy of PFC regions (e.g., Drevets & Raichle, 1998). When lateral PFC regions are engaged, RL-PFC will permit reflective selection among task sets, and DL-PFC and VL-PFC will implement this selection, representing a reconfigured context for responding. The consequences of this new representation are propagated back down the hierarchy, biasing simple approach-avoidance rules in OFC, which plays a more direct role in regulating amygdala activation.

The last PFC region that appears to play a critical role in ER is dorsomedial PFC (DM-PFC; BA 9[medial]). Although the exact function of DM-PFC is heavily debated, this region has repeatedly been shown to be involved in various aspects of reflective emotional processing. In a meta-analysis of emotion, Phan, Wager, Taylor, and Liberzon (2002) found that DM-PFC was involved in many aspects of affective processing, regardless of the valence and sensory modality of the triggering stimulus. Interestingly, this region was much more likely to be activated in studies involving reflectively generated emotion, as opposed to perceptually generated emotion—for example, when people generated an emotional response in the absence of a triggering stimulus (Teasdale et al., 1999), when people monitored their emotional response (Henson et al., 1999), and when people anticipated an emotional response (Porro et al., 2002). In addition, this region appears to play an important role in the understanding of social agents (Frith & Frith, 1999; Gallagher & Frith, 2003; Mitchell, Banaji, & Macrae, 2005; Mitchell, Macrae, & Banaji, 2004), leading Cunningham and Johnson (in press) to suggest that this region may be a polymodal integration area for the complex processing and understanding of emotional information and may be involved in more complex aspects of emotion (guilt, shame, *schadenfreude*) that may drive or be a consequence of emotional regulation. This account relies on a distinction between direct, perceptual processing of stimuli (including rewards and punishers) and indirect processing that is mediated by reflective processing (e.g., *anticipated* rewards and punishers).

A series of studies from our lab that compare the more explicit to more implicit aspects of the emotional evaluation of stimuli allows for comparisons between relatively automatic emotional responses to stimuli and the emotional experience that is modified through ER. Importantly, in these studies, ER is not the person's primary goal per se, but occurs in the service of other goals. For the most part in these studies, participants make either evaluative (Good-Bad) or non-evaluative (Abstract-Concrete; Past-Present) judgments during fMRI (Cunningham, Johnson, Gatenby et al., 2003; Cunningham, Raye, & Johnson, 2004, 2005) or EEG recording (Cunningham, Espinet, DeYoung, & Zelazo, 2005). Following scanning, participants rate each of the stimuli presented to them during scanning on several dimensions, including the extent to which they (a) had an emotional response to the stimulus, (b) experienced attitudinal ambivalence (having simultaneous positive and negative responses) and (c) they attempted to regulate their initial emotional response. Using these ratings as parametric regressors, we have been able to map the relations among brain processing and specific aspects of evaluative or emotional processing.

As would be expected, emotionality ratings correlated with activation in the amygdala and OFC for both Good-Bad and Abstract-Concrete trials—suggesting that the emotional significance of stimuli was processed relatively automatically (see Figure 6, left column). More critical for the discussion of ER as EF, ratings of ER correlated with activation in each of the areas in our proposed model—ACC, OFC, VL-PFC, DL-PFC, and RL-PFC (see Figure 6, middle column). Providing support for the suggestion that VL-PFC is involved in re-weighting of the relevance of information and in selecting information for subsequent processing, we found the greatest VL-PFC and ACC activity for stimuli rated as most ambivalent (Cunningham, Johnson, Gatenby, et al., 2003). In addition, self-reported ER correlated with activation in DM-PFC. Interestingly, and in contrast to the correlations observed for the experience of an emotional response, the correlations between these brain regions and ratings of ambivalence and ER were found to be significantly greater for evaluative as compared to non-evaluative trials. This difference suggests that ER and the processing of complex emotions occurs primarily in the service of deliberate, goal-directed processing.

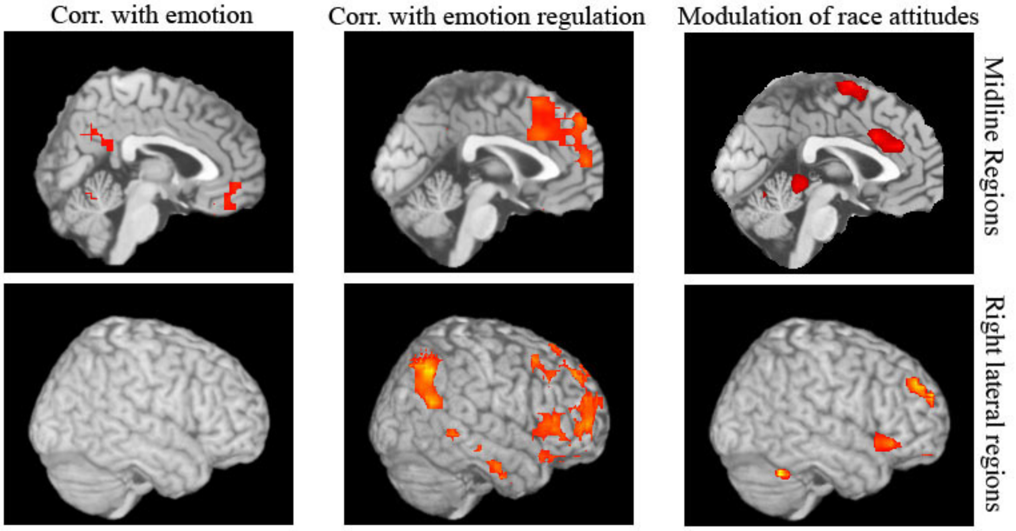

Figure 6. Data depicting the processing of emotional experience and emotion regulation. Data from the right lateral surface and the medial regions are presented for each analysis. Data for the correlation between emotion and emotion regulation are taken from Cunningham, Raye, & Johnson (2004), and data for the modulation of race prejudice are taken from Cunningham, Johnson, Raye et al. (2004).

Similar results were found in an fMRI study of the regulation of prejudice—or ER in the context of attitudes about race (Cunningham, Johnson, Raye, et al., 2004). In most college samples, participants are likely simultaneously to show (a) automatically activated negative behavioral responses to social outgroups and (b) motivation to suppress these feelings in order to display a more socially acceptable response (Cunningham, Nezlek, & Banaji, 2004; Devine, 1989; Plant & Devine, 1998). Thus, on average, people are likely to adopt a goal of inhibiting or suppressing an emotional response that could potentially result in prejudice or discrimination, and they are likely to use EF processes to accomplish this goal. In our study, participants were presented with Black or White faces for either 30 ms or 525 ms. In the 30 ms condition, participants did not report seeing faces, whereas the 525 ms condition allowed sufficient time for the conscious recognition and processing of the face. When participants were not able to see the faces, greater amygdala activation was found to the Black compared to the White faces consistent with the hypothesis that, even for individuals who claimed not to be prejudiced, there was an automatic negative emotional response to members of social outgroups. In contrast, when participants were able to see the faces and had the ability to regulate their emotional response, amygdala activation was significantly reduced and accompanied by activation in frontal regions (see Figure 6, right column). It is important to note that despite the vast differences between these studies, the particular PFC regions found were nearly identical to the regions found to be correlated with self-reported ER in Cunningham, Raye, and Johnson (2004: see Figure 6, middle and right columns, for comparison). Providing further evidence for the involvement of these regions in ER, we found that activity in RL-PFC and ACC was significantly correlated with a reduction in amygdala activation to Black compared with White faces.

It should be noted that ER does not necessarily imply the *inhibition* of a response. Similar to the fMRI studies just discussed, Cunningham, Espinet, DeYoung, and Zelazo (2005) presented participants with valenced stimuli and asked participants to make either Good-Bad or Abstract-Concrete judgments while high-density EEG was recorded. Consistent with hypotheses of hemispheric asymmetries in the processing of emotional stimuli (e.g., Davidson, 2004), greater anterior right sided activity was observed to stimuli rated as bad compared to stimuli rated as good. Interestingly, this effect, which began approximately 450 ms following stimulus presentation, was observed for both Good-Bad and Abstract-Concrete trials. Although the onset of the asymmetry was not influenced by task, the amplitude of the effect as measured later in processing (e.g., 1200 ms post stimulus) was greater for the Good-Bad compared with the Abstract-Concrete trials. This suggests an automatic initiation of emotional processing followed by an amplification of a response as a result of reflective reprocessing of the stimulus (e.g., by lateral PFC).

Key Implications of the New Model

Reseeding. One key proposal of this model is that information about a motivationally significant stimulus is reprocessed iteratively using the same network that was used for the original processing. Specifically, PFC processes foreground specific aspects of information (hence backgrounding others), and these re-weighted representations are used to "reseed" EF processing by influencing ongoing processing of the stimulus. This is accomplished, according this model, by thalamo-cortical connections between lateral PFC and the thalamus that bias attention to particular aspects of the situation as it continues to be processed in real time. As such, EF, and ER, should not be thought of as single processes that act in opposition to emotional processing (e.g., turning off a circuit). Rather, given the iterative nature of EF, the information is likely reprocessed multiple times before a goal state is reached. This highlights an important feature of the ER as EF model: many of the processes involved in ER are the very same processes that are used for emotion generation. Indeed, on this model, successful ER just is the deliberate, goal-directed attainment of a desired emotional state. When this state has been achieved, and the discrepancy between the goal state and the current state is reduced below some threshold, ER will cease.

Implications for development of ER. The growth of PFC follows an extremely protracted developmental course (e.g., Giedd et al., 1999; Gogtay et al., 2004; O'Donnell et al., 2005; Sowell et al., 2003) that mirrors the development of EF. For example, developmental research suggests that the order of acquisition of rule types shown in Figure 4 corresponds to the order in which corresponding regions of PFC mature. In particular, gray matter volume reaches adult levels earliest in OFC, followed by VL-PFC, and then by DL-PFC (Giedd et al., 1999). Measures of cortical thickness suggest that DL-

PFC and RL-PFC exhibit similar, slow rates of structural change (O'Donnell et al., 2005). On the basis of this evidence, Bunge and Zelazo (in press) hypothesized that the pattern of developmental changes in rule use reflects the different rates of development of specific regions within PFC. The use of relatively complex rules is acquired late in development because it involves the hierarchical coordination of regions of prefrontal cortex—a hierarchical coordination that parallels the hierarchical structure of children's rule systems and develops in a bottom-up fashion, with higher levels in the hierarchy operating on the products of lower levels.

To the extent that PFC is involved in ER, the development of ER should also be a protracted process, and may be informed by research on the development of EF. A good deal is now known about the development of cool EF (see Zelazo & Müller, 2002, for review), but relatively little is known about the development of hot EF. One key line of work, however, comes from Overman and his colleagues (Overman et al., 1996), who demonstrated age-related improvements in performance on object reversal in infants and young children. In addition, these authors found that prior to 30 months of age, boys performed better than girls—a finding consistent with work showing that performance on this task develops more slowly in female monkeys than in male monkeys, and that this sex difference is under the control of gonadal hormones (Clark & Goldman-Rakic, 1989; Goldman, Crawford, Stokes, Galkin, & Rosvold, 1974). This suggests that there may be a similar neural basis to sex differences in ER.

Kerr and Zelazo (2004) assessed hot EF in slightly older children, using a version of the Iowa Gambling Task (Bechara et al., 1994). Children chose between (a) cards that offered more rewards per trial but were disadvantageous across trials due to occasional large losses, and (b) cards that offered fewer rewards per trial but were advantageous overall. On later trials, 4-year-olds made more advantageous choices than expected by chance whereas 3-year-olds (and especially 3-year-old girls) made fewer. Three-year-olds' behaviour on this task resembled that of adults with damage to OFC, suggesting that the task may provide a behavioural index of the development of orbitofrontal function. Subsequent work explored the basis of 3-year-olds' poor performance, identifying a role for working memory (Hongwanishkul et al., 2005) and demonstrating that even 3-year-olds develop somatic markers as indicated by anticipatory skin conductance responses (SCRs) prior to making disadvantageous choices (DeYoung et al., 2005). Paradigms like this one may be used to explore the role of hot EF in ER (e.g., see Lamm, Zelazo, & Lewis, in press; Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006).

Conclusion

In this chapter, we provided a new model of ER that spans Marr's (1982) three levels of analysis—computational (concerning what ER accomplishes), algorithmic (dealing in more detail with the way emotion-relevant information is represented and how it is processed during ER), and implementational (examining the neural basis of ER). Naturally, this model is overly simple; the processes involved in ER are only beginning to be understood. Nonetheless, the model makes specific claims at all three levels of analysis, and may provide a useful stimulus for future research on ER. In addition to testing hypotheses derived from the model (e.g., developmental constraints on ER), future research might usefully explore whether different strategies of ER rely on different aspects of EF and how the processes underlying ER overlap with those involved in the experience of complex social emotions (i.e., emotions that likely require relatively high levels of consciousness). Overall, however, we hope that this model demonstrates how an understanding of basic processes of EF may shed light on critical aspects of emotion, including the phenomenological experience of emotion and the dynamic regulation of this experience.

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