

Integration of emotion and cognitive control

A neurocomputational hypothesis of dynamic goal regulation

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This chapter sketches how one aspect of a theory of cognitive-emotional interactions might develop, with a particular emphasis on computational constraints. In general, the prefrontal cortex (PFC) might serve as a neurocomputational substrate for integrating information about goal-related emotional states with the cognitive control of behavior by actively maintained goals. The specific possibility we consider in detail concerns the relation between emotional and cognitive information processing: that these processes are likely to interact in a selective or functionally integrated rather than non-selective manner. In particular, goal management in a dynamic environment in which there are unpredictable threats and rewards is an important self-regulatory problem that might have been solved computationally, in part, through an integration of cognitive and affective processes in lateral PFC (Gray in press; Gray 2001; Gray, Braver, & Raichle 2002; Tomarken & Keener 1998).

The *cognitive control* of behavior refers to an important set of psychological functions (see Braver & Cohen 2000; Norman & Shallice 1986; Posner & Snyder 1975): the ability to develop and carry out temporally extended plans of action, especially novel ones, to do so in the absence of sensory cues, to resist distraction or interference, and to update goals and subgoals in a flexible manner. Cognitive control is clearly not a unitary process; rather, many subfunctions contribute in a coordinated manner. Working memory, or maintaining and manipulating information actively in mind (Baddeley & Hitch 1974), is an important aspect of cognitive control, and itself has component processes.

Emotional states might modulate components of cognitive control to allow for the temporary, adaptive enhancement of some subfunctions over others (Gray 2001, in press). In the hypothesis presented, we focus on mechanisms for updating goals in a flexible manner, viewing unpredicted threats and rewards as critical events which require flexibility and efficiency in goal management. The proposed role of emotion is to exert a "bottom-up" influence on the functioning of the PFC (especially WM subsystems), thereby modulating the efficacy of active goals in guiding behavior. The key aspect we highlight concerns the ability of such regulation to be both context-dependent and yet require only a bottom-up mechanism. Such a computational architecture could support the adaptive prioritization of goals in environments having unpredictable threats and rewards.

To our knowledge, selective effects of emotion on cognitive control have been little considered with reference to a theoretical basis (but see Gray in press; Gray 2001; Gray et al. 2002; Tomarken & Keener 1998). That is, models in which emotional selectivity is implicit have typically described patterns of association rather than emphasized how psychologically adaptive, functional relations among components might give rise to the observed associations. The model we present in this chapter is based in part on connectionist neural network models of brain function. In such models, implementing different kinds of processes typically requires some computational specialization, which in turn promotes specialization within neural systems (O'Reilly, Braver, & Cohen 1999; Rueckl, Cave, & Kosslyn 1989). That is, when there are inherent computational tradeoffs, different brain regions tend to become specialized for handling incompatible aspects of the overall problem. Applying this logic to emotion suggests that there might be a functional reason for hemispheric specialization for approach- and withdrawal-related emotion. Specifically, asymmetries for both emotion and cognitive control might enable selective effects of emotion on cognitive control, thereby allowing for context-dependent regulation of cognitive control by emotion.

The existence of prefrontal brain asymmetries for both emotion and cognition separately are consistent with the idea that emotional states might modulate cognitive control on a hemispheric basis (Heller 1990; Heller & Nitschke 1997; Tomarken & Keener 1998), thereby supporting selective effects of emotion on higher cognition (Gray, in press; Gray 2001; Gray, Braver, & Raichle 2002). In humans, lateral PFC is somewhat specialized by hemisphere for aspects of cognitive control, e.g., domains of working memory (D'Esposito et al. 1998; Smith & Jonides 1999), sustained attention (Cabeza & Nyberg 2000; Pardo, Fox, & Raichle 1991), and other functions (Banich 1997; Hellge

1993). A largely separate line of work has suggested that the PFC is also somewhat specialized by hemisphere for aspects of subjectively experienced emotion (namely, approach- and withdrawal-related emotional states: Davidson 1995; Fox 1991; Sutton & Davidson 1997). This has been supported by a recent meta-analysis of neuroimaging studies of emotion (Murphy & Lawrence 2001), and by direct recordings from neurons using depth electrodes in humans during induced emotional states (Kaufman et al. 2001). Approach states tend to be associated with greater neural activation in left anterior areas relative to right, and withdrawal states with greater right activation relative to left. Given evidence for asymmetries, hemispheric differences are a possible mechanism supporting selective effects, although need not be the only one (e.g., dorsal-ventral distinctions are also important, Liotti & Tucker 1995).

Our larger argument depends on the existence of selective effects of emotion on cognitive control. There are two empirical issues: whether selective effects are possible, and whether a hemispheric basis is responsible. In our work (Gray 2001; Gray et al. 2002), selectivity is of primary interest while hemispheric differences are secondary (providing a possible mechanism for selectivity). In related work, hemispheric differences have been emphasized (Bartolic, Basso, Schefft, Glauser, & Titanic-Schefft 1999; Heller 1990; Heller & Nitschke 1997). Asymmetries might make sense computationally, and we elaborate this possibility in some detail to help make the discussion of a goal-regulation architecture more concrete. However, the hemispheric hypothesis about the mechanism supporting selectivity should be understood as empirically separable from and secondary to our main interest in selectivity.

We first present evidence for emotional-cognitive integration, focusing on selective effects of emotion on cognitive control, and then a neurocomputational hypothesis in which this form of integration holds a pivotal role.

Selective effects of emotion on cognitive control: Evidence for integration

Are the effects of emotion on cognitive control diffuse, general, or otherwise non-specific, or can they be selective, in the sense of influencing some processes and not others? Selectivity implies a more complex functional organization, as it necessitates the existence of a mechanism whose input includes information about emotional state and cognitive demands, and whose output is not determined exclusively by one or the other, nor by main effects of one on the other, but also by both conjointly (i.e., their interaction). The clearest evidence for a selective effect would be a double dissociation in which cognitive control de-

depends on the emotional context. Such a selective effect would logically imply a true interaction at some point of processing (cf. Sternberg 1969). An interaction means that, at some point, cognitive and emotional information must be integrated to permit a contextual dependence of one on the other. In this section, we briefly present data from experiments designed to test the hypothesis that selective influences of induced emotion on cognitive control are possible.

In three experiments (Gray 1999; Gray 2001), participants had a standard emotion induction (watching 9–10 minute video) and then performed a verbal or nonverbal (spatial) version of a computerized cognitive control task (n-back tasks: Braver et al. 1997) likely to recruit lateralized working memory systems (D'Esposito et al. 1998; Smith & Jonides 1999). All three experiments showed the predicted effect: a significant two-way interaction on performance between the type of task (verbal, nonverbal) and the type of video preceding it (approach, withdrawal). The results are illustrated in Figure 1. Spatial performance was impaired by an approach state relative to the withdrawal state, and the opposite held for the verbal task. Self-reported ratings confirmed the emotion induction and showed that the emotional videos were matched for arousal. Moreover, the crossover interaction was significantly stronger for participants finding the tasks more difficult than for those finding them less difficult. This is of note because individual differences in performance on working memory tasks reflect mainly differences in controlled attention (for a review, see Engle, Kane, & Tuholski 1999), suggesting the effect of emotion was specific to cognitive control. These behavioral data are strong evidence for a selective effect,

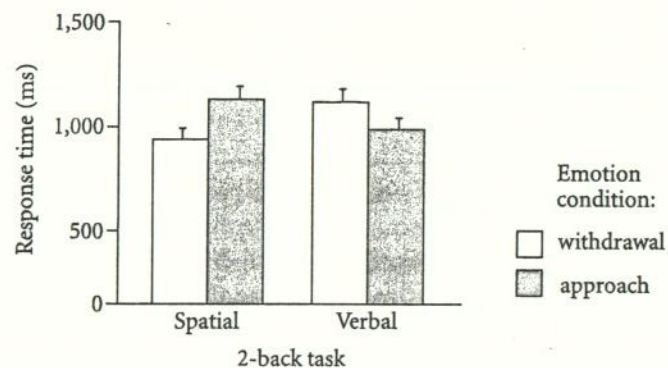


Figure 1. Response times during n-back working memory tasks: spatial or verbal task following approach or withdrawal emotion induction. From Experiment 2, Gray (2001); redrawn with permission, ©American Psychological Association.

and imply the existence of cognitive-emotional integration at some point of processing.

A limitation of these studies was relying on individual differences in overall performance to suggest that the effect was specific to cognitive control. However, Moore and Oaksford (in press) found that induced emotion had the opposite effects on verbal and nonverbal tasks not strongly requiring working memory (visual search, word association). Visual search was enhanced by a positive mood, and word association enhanced by a depressed mood, a crossover interaction in the opposite direction. These results further suggest specificity of the effect of emotion on the n-back tasks to cognitive control.

The selective effect may have been mediated on a hemispheric basis (Gray 2001; Heller 1990). That is, numerous other studies have shown hemispheric differences in processing during verbal versus spatial tasks (see Smith & Jonides 1999) and approach versus withdrawal emotions (see Davidson 1995). We have recently found evidence consistent with this hypothesis using functional magnetic resonance imaging (fMRI, Gray et al. 2002). In an initial behavioral study using verbal (word) and nonverbal (face) versions of an n-back task, the expected crossover interaction in performance was found to hold with these stimuli, again consistent with a hemisphere-based interpretation. In the fMRI study, 14 participants were scanned while they were performing the n-back tasks immediately after having viewed one of the emotional videos. The same behavioral effect held for these participants. Dorsolateral PFC (DLPFC), which is known to be critical for cognitive control, showed the expected hemispheric asymmetry for stimulus type, with words leading to greater left activity and faces to greater right activity. DLPFC also showed hemispheric asymmetry for emotion. Most critically, a third area in DLPFC showed a crossover Stimulus \times Emotion interaction, with the pattern of activity related to behavioral performance. The crossover interaction is further evidence for integration of emotion and cognition. Thus lateral PFC is sensitive to the conjunction of emotional state and cognitive task demands (as has been suggested for medial PFC: Bechara, Damasio, Damasio, & Anderson 1994; Damasio 1994; Luu, Collins, & Tucker 2000; Simpson, Drevets, Snyder, Gusnard, & Raichle 2001a; Simpson, Snyder, Gusnard, & Raichle 2001b). The separate hemispheric asymmetries for stimuli and emotion that were also found in PFC suggest that the integration is in fact computed in lateral PFC. Whatever the mechanism may be that computes the interaction for a particular cognitive control function, it effectively integrates information about on-going emotional state with the demand for cognitive control in order to do so.

In sum, behavioral and neuroimaging evidence suggests that selective effects of emotion on cognitive control are possible. An integration of emotional and cognitive information appears to be computed and represented in lateral PFC. A hemispheric basis for these effects is a possible explanation, although has not been definitively shown and other explanations are possible. What is critical for the following argument is that selective effects occur, because this implies some integration of emotional state and cognitive control processes at some point of processing. We next focus on the question of why such selectivity and integration might be useful.

Dynamic goal management: A need for integration?

In this section, we argue that the integration of emotional state with cognitive control is likely to be adaptive. Adaptive is meant in the psychological sense of promoting function. It might also be evolutionarily adaptive, but for pragmatic reasons the hypothesis concerns only computational efficiency. This of itself will be a somewhat speculative argument because not all aspects of the model are instantiated in a computer program. Some aspects have been instantiated: those related to the active maintenance of context information that guides behavior (Braver & Cohen 2000). Goal representations are an important kind of context information. While we believe that hemispheric specialization and selective modulation by emotional state could be incorporated into this model and would bear out the general conclusions, this awaits demonstration.

The argument concerns the computational requirements of goal management in a dynamic environment. Not all goals are appropriate in all situations, and in particular, a good goal in the wrong context can be disastrous (e.g., continuing to forage for food despite the sudden appearance of a predator). When conditions change and so alter the balance of impending reward and threat, the appropriateness of active goals is likely to change as well. For this reason, the ability of goals to control behavior should depend in part on the context. At times, the relevant context may be strongly emotional in nature, signaling the presence of unexpected reward or threat. This analysis suggests a computational need for a mechanism that can provide an emotional-context-dependent regulation of active goals. The idea that one function of emotion is to help mediate priorities is widely held, but to our knowledge it has not been elaborated in detail commensurate with its probable complexity and importance for self-regulation (see Carver & Scheier 1990; Carver, Sutton, & Scheier 2000; Ekman

& Davidson 1994; Gray 1990; Gray 1999b; Lang 1995; Lazarus 1991; Simon 1967; Tomarken & Keener 1998).

Goals can be considered a kind of mental representation that engage cognition and action in the service of making a particular, motivated state of affairs more likely to come about through one's own efforts. For goals to bias behavior adaptively, suitable representations need to be maintained in a manner that can influence self-regulatory behavior. The influence that goals have on behavior can be diverse, e.g., manifesting as selective attention, sustained attention, inhibitory control, and so on, although this does not necessarily imply separate mechanisms (see Braver & Cohen 2000). Because goals need to exert a powerful influence on cognitive control, there must also be some way to ensure that they are appropriate given other aspects of a situation. That is, some mechanism is necessary to effect dynamic adjustments in goal priority in response to changes in external conditions.

We focus on one possible way that dynamic prioritization could be instantiated: the active maintenance of goal representations in working memory subsystems, plus a selective modulation of these subsystems (and hence the active representations within them) by approach-withdrawal emotional states. The relative strength of an active goal's representation would determine how effectively that goal could influence behavior. The key idea is that a dynamic goal management system would benefit from separating the active maintenance of approach and withdrawal goal representations, and from the selective regulation of these active maintenance systems by emotional states. To achieve selectivity, such a system would benefit from or even require a computational architecture that integrates emotional state with active maintenance to provide situationally appropriate regulation.

The term *goal* is intended to denote a motivationally-relevant representation that, when actively maintained, constrains or otherwise coordinates the control of cognition and behavior to fulfill the corresponding motivation. Goals are representations that help configure the rest of the overall perceptual-cognitive-behavioral control system. A goal constrains what part of that system is most relevant for further processing. For example, in the Stroop task, the participant's goal (set up by the task instructions) is to report the color of printed words regardless of the semantic content of the words. The semantic content can refer to colors, thereby creating response conflict between the goal (report the color) and a prepotent response (read the word). As used here, goals need not be recognized explicitly as goals, nor need be conscious (cf. Bargh & Chartrand 1999), although can be. Rather, goals direct or guide the focus of attention, and are not usually the object of attention. Goals are an impor-

tant kind of context information that bias other on-going processing (Braver & Cohen 2000). Multiple goals can be active simultaneously, many more can be activated by retrieval cues (Gollwitzer 1999), and complex or higher-order goals typically require the implementation of subgoals. Such goal hierarchies are very important, but beyond the scope of the current model (see Carver & Scheier 1990; Koechlin, Basso, Pietrini, Panzer, & Grafman 1999).

To a first approximation, most and perhaps all goals can be considered to be associated with approach- or withdrawal-related motivations (for a more nuanced discussion, including the possibility of the same goal having conflicting motivational implications at different levels in a hierarchy, see Carver & Scheier 1990). It is possible to distinguish between what might be termed explicit or pure approach goals (e.g., "take two steps forward") versus implicit or approach-consistent goals in which a pure approach component would be a necessary subgoal (e.g., "oooh, jelly donut... must have", leading to a first subgoal "take two steps forward" followed by "pick up donut" and "ingest donut"). To simplify the discussion we do not elaborate this distinction, although it could be useful in further refinements of the model. For withdrawal-related motivation, the term goal may seem inappropriate, but the intended sense applies equally for approach and withdrawal motivation.

The core argument is that approach and withdrawal emotional states might differentially modulate WM subsystems in order to regulate the strength of approach- and withdrawal-related goal representations held within them. Stronger active representation in working memory should afford greater influence over behavior. There are six key points, each elaborated in a separate section:

1. Approach and withdrawal are two important dimensions of motivation. The motivational implications of on-going interactions with the environment can come to be reflected in approach- and withdrawal-related emotional states.
2. Active goals are maintained in working memory, allowing them to coordinate thought, affect, and behavior by serving as context information, with approach goals in one subsystem and withdrawal goals in another subsystem.
3. Approach-withdrawal states can have selective effects on working memory subsystems in order to selectively regulate the active goals within the different subsystems.
4. Multiple goals can be simultaneously active, even inherently conflicting ones, and so co-exist in some balance. A critical function of approach-

withdrawal emotion is to tip the balance in favor of one or the other class of goals when it is important to do so.

5. Approach and withdrawal goals are incompatible in terms of their regulation by emotion. Physical segregation of active approach-withdrawal goal representations would make a physiological mechanism for their selective regulation more simple.
6. Lateral PFC is a plausible neural and computational substrate for the active maintenance and regulation of goals by emotional state, given (a) lateral PFC involvement in WM, goal-directed behavior, and emotion; (b) hemispheric specialization in PFC for both emotion and WM; and (c) integration of emotion and WM in lateral PFC.

Approach and withdrawal emotion

In general terms, emotions are brief, relatively strong states that are triggered by specific events having significance for the organism (see Ekman & Davidson 1994; Lazarus 1991). The pervasiveness of approach and withdrawal motivation across species (Lima & Dill 1990; Schneirla 1959) forms part of the theoretical basis for postulating approach and withdrawal as two major classes of emotion (Davidson, Ekman, Saron, Senulis, & Friesen 1990; Fox 1991; Lang, Bradley, & Cuthbert 1990). Such emotions are strongly goal-directed.

The events that trigger an emotion can be real and on-going, anticipated, reconstructed from memory, or even the product of fantasy. In Figure 2, these triggering events are denoted collectively as the Situation. When a stimulus or event suggests a threat, the resulting state is unpleasant and withdrawal motivated (e.g., fear, anxiety). If the event is expected to be favorable or rewarding, the resulting state is pleasant and approach motivated (e.g., desire, enthusiasm). Pleasant but post-goal attainment states (e.g., satiation) are not approach related despite positive emotional valence, because they lack goal-directedness (Davidson 1998a). Similarly, some unpleasant states are not goal-directed (e.g., disappointment, sadness) and so are not withdrawal related. This article is concerned only with emotional states that involve pleasant-approach motivation or unpleasant-withdrawal motivation, and is agnostic about emotions that are not goal directed, e.g., contentment, fulfillment, sadness, or disappointment.

Regulation of goals by emotional state

It is impossible for an organism to simultaneously approach and withdraw from something. The incompatibility of approach and withdrawal behavior

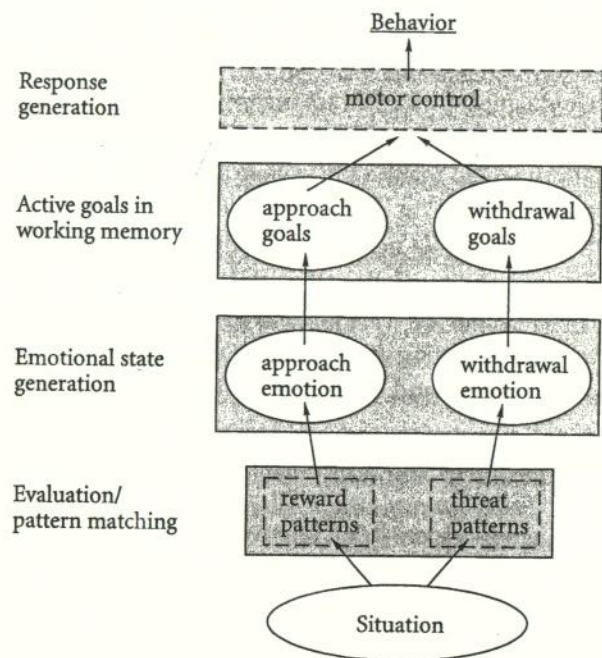


Figure 2. Schematic outline of emotion-related processing stages. These stages are intended only to help illustrate points important for the present argument, rather than describe a general or complete architecture of emotional cognition. The stage most relevant to the proposed architecture is that of active goals in working memory. This stage allows for both active maintenance in attractor states (via recurrent connections), and bottom-up, situation-dependent regulation (via emotional states).

in no way eliminates the potential for motivational conflict: Strong motivations to approach and withdraw can be held simultaneously (Carver & Scheier 1990; Miller 1944). For this reason, a dilemma faced repeatedly in both individual and evolutionary history is: given the current situation, are the advantages to be had from approach behavior greater than those from withdrawal? Once Evaluation processes (Figure 2) settle in favor of one alternative, the motivational conflict is reduced. Cognitive, affective, and motor control should be coordinated and come to reflect and implement the assessment of the course of action that appears better (regardless of whether the assessment is objectively correct). Emotional states are well suited to play a modulatory role that can bring about such prioritization, coordinating multiple systems in parallel. Selectivity would be useful for enhancing some functions but not others, depending on the particular emotional state.

Evaluations of potential rewards and threats in the environment are routinely computed (Figure 2, Evaluation stage). Simple pattern matching or feature detection could suffice at the earliest stages, even operating outside of awareness (LeDoux 1996; Morris, Ohman, & Dolan 1998; Whalen et al. 1998b). If some relevant aspect of the situation is novel, anomalous, or ambiguous (Whalen 1998), it is likely to trigger further processing, including evaluations that are focused, elaborated, and potentially conscious especially as more information is sought and obtained from the environment and associative memory. Given ambiguity, both withdrawal and approach motor programs are primed for subsequent activation. If the outcome of the Evaluation process is that the situation is interpreted as a threat, withdrawal motor programs are activated and approach programs inhibited. The resulting modulation of the brain-plus-body state profile constitutes a withdrawal-motivated emotional state (Figure 2, Emotion Generation stage; motor priming is not illustrated).

In almost any situation, multiple goals are active to varying degrees, and so there is typically some on-going conflict or tension between goals (Figure 2, Active Goals stage). In a withdrawal state, withdrawal goals need greater access to high-level control and approach goals less access. Previously active approach goals should be dampened, whereas withdrawal goals including those activated by the withdrawal program should be strengthened. The strengthening or weakening of goal representations is postulated to bring about adaptive cognitive and behavioral responses by modulating the ability of an actively maintained goal to influence motor control. Similarly, approach states are postulated to prioritize approach goals and dampen withdrawal goals. Although we expect considerable similarity, the symmetry is not perfect. For example, the strength of withdrawal-related motivation falls off more quickly than approach-motivation with increasing distance (Miller 1944). This steeper slope for withdrawal holds quite generally, and strongly suggests two underlying systems (Cacioppo, Gardner, & Berntson 1999). Moreover, there are large individual differences in the strength of threat and reward systems (Carver et al. 2000; Gray 1991; Kagan, Reznick, & Snidman 1988; Sutton & Davidson 1997).

A function of emotional states is to bias the on-going tension between approach and withdrawal classes of goals when the situation is sufficiently critical. Further prioritization of different specific goals within the same motivational class would also be useful, but is beyond the scope of the current model. Many theoretical views concerning the function(s) of the more basic emotions hold that, as almost inherent in the definition of emotion, prioritization occurs in some form (Ekman & Davidson 1994; Gray 1990; Gray 1999b; Lang et al. 1990; Lazarus 1991; Schwarz 1990; Simon 1967). However, there are few em-

pirical investigations. This widely held assumption might be tractable in terms of specific effects of emotional states on working memory.

Representation of goals in working memory

WM is the process for holding and manipulating information actively in mind, and is well suited to hold representations of goals. In the sense of the term goal used here (Braver & Cohen 2000), a hard distinction between goals and other forms of information to be maintained actively is likely a false dichotomy (see also Gallese & Goldman 1998). In Braver and Cohen's (2000) model, PFC actively maintains context information — mental representations that can perform a general biasing function by providing top-down support, e.g., for encoding information from one perceptual dimension rather than another (e.g., in the Stroop task), for task-relevant information in the face of competing distractors (e.g., for the item seen two trials ago in a 2-back task, rather than the item seen either one or three trials previously). Braver and Cohen explicitly point out that goals have this function, and note that other kinds of context information can as well. A WM subsystem dedicated for goal maintenance but not context information is unlikely.

The original model of human WM (Baddeley & Hitch 1974) posited three distinct systems for actively maintaining and manipulating information. Two subsystems provide segregated maintenance of phonological and visuospatial information, with overall coordination by a modality-independent central executive. The central executive component of working memory is specifically conceptualized as being independent of storage modality, being involved in planning and the coordination of action (see Norman & Shallice 1986). A recognized limitation of this influential model concerns the mechanisms that implement the control functions ascribed to the central executive (for discussion, see Baddeley 1996).

The inclusion of context information as a component of WM (Cohen & Servan-Schreiber 1992) suggests a mechanistic way to model how cognitive control might be regulated by bottom-up processes, avoiding the need to posit a central executive (Braver & Cohen 2000; Braver, Cohen, & Servan-Schreiber 1995). Braver and Cohen's theory is instantiated as a gated-attractor (neural network) model. The computationally realized mechanism can a) learn to appropriately select which items need to be maintained using a reward-like mechanism for feedback about performance (modeled on dopamine function); b) hold active for arbitrary periods of time the items that are critical for constraining responses to other events (i.e., the information that acts as contextual

constraint on subsequent actions); c) protect such information against interference during the delay period; and d) update such information as needed (Braver & Cohen 2000). The model is neurobiologically plausible, as shown by converging evidence from normal aging, brain imaging, schizophrenia, and amphetamine challenge (Braver 1997), and studies of dopamine and reward prediction (see Schultz, Dayan, & Montague 1997) and dopamine-WM interactions (e.g., Luciana, Depue, Arbisi, & Leon 1992; Sawaguchi & Goldman-Rakic 1994). In the model, transient fluctuations in dopamine signals (which are biologically realistic, modeled on responses to unpredicted reward) provide overall, bottom-up control of network dynamics.

Because other evidence suggests a relationship between dopamine and positive emotion (Ashby, Isen, & Turken 1999; Depue, Luciana, Arbisi, Collins, & Leon 1994; Luciana et al. 1992), it might be possible to incorporate emotional modulation into the Braver and Cohen model. Specifically, neuromodulators might carry information about emotional states, setting attractor dynamics that prioritize some high-level functions over others. Small changes in the neural firing of brainstem neuromodulator nuclei that project diffusely could lead to global, sustained effects on information processing dynamics in cortical networks critical for higher cognition and goal-directed behavior (cf. Hasselmo & Bower 1993; Hobson & Stickgold 1995). To speculate boldly, diffuse-projecting neuromodulators might suffice as a bottom-up mechanism able to selectively regulate cognitive control. Dopamine (Luciana, Collins, & Depue 1998; Luciana et al. 1992), norepinephrine (Arnsten & Goldman-Rakic 1987), serotonin (Luciana et al. 1998), corticosteroids (Lupien, Gillin, & Hauger 1999), and acetylcholine (Furey, Pietrini, & Haxby 2000; Robbins et al. 1997) have been shown to modulate WM performance in human participants. Computational models have suggested a link between dopamine, pleasant emotions, and modulation of higher cognitive functions (Ashby et al. 1999).

Separate representation to facilitate regulation

A physical separation of mechanisms for approach and withdrawal information processing could be beneficial for computational reasons. Different benefits might accrue at each of three stages of approach-withdrawal processing shown in Figure 2: Evaluation, Emotion Generation, and Active Goals.

First, at the Evaluation stage, we posit separate subsystems for the initial processing or pattern matching of approach cues (potential reward) and withdrawal cues (potential threat). Two subsystems are likely to be more accurate and useful than a single combined system that is sensitive only to the difference

or relative balance between reward and threat. The reason is that there is an important difference between a high-conflict choice, with high reward but also high threat, and a trivial choice, with low reward and low threat. For a high-conflict choice, gathering more information, and so on, would be important, but would be unimportant and even wasteful for a trivial choice. Consider a 2-dimensional space with an approach dimension orthogonal to a withdrawal dimension, with the strength of motivation going from low to high on each dimension. A high-conflict choice involves high approach and high withdrawal, whereas a trivial choice involves low approach and low withdrawal. Representation as one dimension (a continuum of the approach-withdrawal difference) would not allow an easy recovery of the degree of conflict. Separate initial representations of approach and withdrawal (two dimensional) would allow an extraction of conflict information.

In previous work, we have proposed a hypothesis relating conflict monitoring to cognitive control (Botvinick, Braver, Carter, Barch, & Cohen 1998; Carter et al. 1998). In particular, the anterior cingulate cortex (ACC) is postulated to evaluate the demand for cognitive control by monitoring for the occurrence of conflict in on-going information processing. By conflict, we mean interference or interactions between different information processing pathways. In a series of computer simulation studies, we provide a detailed examination of the theoretical consequences of this hypothesis (Botvinick et al. 1998). One of the predictions that arises from such a theoretical position is that the ACC should be engaged whenever two or more incompatible responses are simultaneously activated. Recent neuroimaging studies of cognitive tasks have provided direct empirical support for this prediction (Barch et al. 2001; Barch, Braver, Sabb, & Noll 2000; Botvinick, Nystrom, Fissel, Carter, & Cohen 2001; Braver, Barch, Gray, Molfese, & Snyder 2001; Carter et al. 2000; Casey et al. 2000; MacDonald, Cohen, Stenger, & Carter 2000). In this context, it is interesting that some areas of ACC are related to emotion (Bush, Luu, & Posner 2000; Devinsky, Morrell, & Vogt 1995; Whalen et al. 1998a). A possibility is that ACC might be particularly sensitive to emotional conflict, as much or perhaps even more so than to emotion. Emotional conflict might be ubiquitous in experiments in which participants are asked to voluntarily engage with negatively valenced stimuli or in difficult tasks, which are often subjectively unpleasant and provoke performance anxiety. This novel hypothesis (see also Gray & Braver, in press) has yet to be tested, but if supported could potentially provide a unifying conceptual basis of anterior cingulate function.

To better preserve information about the degree of emotional conflict, the initial evaluation of the benefits of approach and withdrawal should not cancel

each other out or otherwise interfere before the two have been computed. Representations of each separately would be more informative than a single representation of the difference (a relative representation). Thus in terms of initial evaluation, approach and withdrawal are more usefully computed as two dimensions, each ranging from low activation to high activation. Considerable evidence suggests two underlying systems (see Cacioppo et al. 1999; Carver et al. 2000; Miller 1944).

Splitting a network by reducing the connections between subsystems reduces interference between computationally incompatible functions that process the same input. Such splitting can yield a measurable computational advantage (Rueckl et al. 1989). For example, in computing *where* something is and computing *what* something is from visual input, the information critical to one computation is irrelevant to the other. The key idea, supported by the simulations, is that splitting a network removes connections that can only cause interference – those that cannot contribute to performing the computation needed, but could contribute irrelevant information. These considerations suggest that implementing two subsystems for the extraction of approach and withdrawal information would be more efficient computationally. The *what-where* distinction is found not only in dorsal versus ventral visual streams (Ungerleider & Mishkin 1982), but is also maintained in WM (Ungerleider, Courtney, & Haxby 1998).

Second, segregation of approach-withdrawal processing would also be useful during an Emotion Generation stage (Figure 2) because it would permit reciprocal inhibition between two systems. Reciprocal inhibition provides more flexibility and precision in the degree of control that a system can achieve. Reciprocal inhibition necessitates having more than one subsystem. In principle, one subsystem that computed a single dimension (from high approach to neutral to high withdrawal) cannot provide as much flexibility and precision as two subsystems that are mutually inhibitory. These are inherent benefits of reciprocal inhibition in control systems, and there is evidence for reciprocal inhibition between approach and withdrawal emotion subsystems (Lang et al. 1990; Solomon & Corbit 1974).

Third, and most critically, separate representation of approach and withdrawal classes at the Active Goals stage (Figure 2) would simplify the selective regulation of active goals by emotional states. The physiological mechanism for regulation could be simpler to implement given representations separated physically on the basis of motivational class. Non-specific modulation would be sufficient to influence the entire class. Having systems that are enmeshed physically would require considerable specificity and therefore complexity in

the regulatory mechanism. The reason is that, at the stage of active maintenance, there is not likely to be a functional distinction between approach or withdrawal goals – they are both simply information that has to be maintained actively. WM performs a general holding function, effectively blind to its own contents; response generation subsystems are posited to operate differentially depending on the contents of WM. Because the function of WM is the same regardless of the functional implications of the contents, a mechanism for the regulation of that content would be complex to implement if it depended on the specific content. Physical segregation is likely a simpler (and therefore more robust) mechanism for selective, bottom-up regulation on the basis of the motivational class of the emotion (approach, withdrawal). Complex mechanisms are probably possible, but a compelling reason would be needed to justify the additional physiological complexity and greater proneness to errors that this would likely entail.

To recap this section of the argument, segregation of approach-withdrawal processing would be useful at three stages of processing (Figure 2). Computational efficiency would be enhanced in Evaluation stages, because two orthogonal dimensions can carry more information about conflict. Control would be enhanced in the Emotion Generation stage, because reciprocal inhibition between two subsystems is more flexible and precise than a single system acting alone. These two kinds of segregation are likely to be reflected in the Active Goals stage. Most critically, approach and withdrawal goals are strongly incompatible in terms of regulation by emotional state, given the incompatibility of approach and withdrawal behavior. When approach goals are prioritized, withdrawal goals should be dampened, and vice versa. Which class of goals is prioritized at any one time should be situation dependent, and should be amenable to flexible updating. These three considerations provide a theoretical basis for expecting a physically separate maintenance of approach versus withdrawal representations of active goals.

Lateral prefrontal cortex as a substrate

The aim of this section is to suggest on empirical grounds that hemispheric specialization in PFC provides a suitable, two-part neural substrate for the active representation and regulation of goals. Although hemispheric specialization is not the only possible way to achieve physical separation between subsystems for either emotion or WM, to our knowledge it is the one that is the most consistent with constraints provided by neurobiology. This section therefore reviews evidence for hemispheric specialization of emotion and WM in PFC.

In humans, lateral PFC is critical for cognitive control. These functions include planning, reasoning, voluntary action, and decision making – all of which involve goal directed activity. PFC is large and many functions have been proposed for all or part of it: working memory (Goldman-Rakic 1987; Smith & Jonides 1999), context and cognitive control (Braver & Cohen 2000; Cohen & Servan-Schreiber 1992), the cross-temporal organization of behavior (Fuster 1997), the voluntary control of behavior (Passingham 1993), and aspects of personal and social decision making (Damasio 1994; Tucker, Luu, & Pribram 1995). As shown by neuroimaging studies in humans (see Braver et al. 1997; D'Esposito et al. 1998; Smith & Jonides 1999), critical areas for WM include dorsal PFC (Brodmann's Areas [BA] 46, 9) and ventral PFC (BA 44, 45, 47).

Lateralization of experienced emotion. Diverse evidence suggests a prefrontal asymmetry related to subjectively experienced approach and withdrawal emotion (see Davidson 1995; Fox 1991; Gray, in press). Patients with damage to left PFC more easily become depressed, whereas those with right damage tend to display inappropriately indifferent or even positive affect (Robinson, Kubos, Starr, Rao, & Price 1984). As shown in normal participants by electroencephalogram (EEG) recordings, relatively greater left prefrontal activity is associated with approach states and traits; relatively greater right activity is associated with withdrawal states and traits. Induced (state) changes are deflections away from a baseline, trait-like asymmetry, which is stable within individuals yet quite variable across individuals (Sutton & Davidson 1997; Tomarken, Davidson, Wheeler, & Doss 1992). Phasic asymmetry from induced emotion is superimposed upon large individual differences in the baseline degree of asymmetry. The anterior asymmetry is found for induced emotional states not only in adults but also in neonates, 10 month olds, and non-human primates. A functional neuroimaging study specifically tested for the emotion asymmetry using fMRI and controlled for arousal (Canli, Desmond, Zhao, Glover, & Gabrieli 1998). The asymmetry was present as shown by the numbers of activation clusters and the extent of activation.

The evidence suggesting an asymmetry is generally reliable. However, there are also exceptions (see Gray, in press; Heller & Nitschke 1998), including findings of no asymmetry (Hagemann, Nauman, Becker, Maier, & Bartussek 1998; Reid, Duke, & Allen 1998) or asymmetries in the opposite direction (Chua, Krams, Toni, Passingham, & Dolan 1999; Shin et al. 1997). Conceptual and methodological considerations are likely to be important (Davidson 1998b), as well as moderating factors (Heller & Nitschke 1998; Reid et al. 1998) and

greater understanding of what the asymmetry reflects mechanistically (Gray 2002; Gray, in press; Tomarken & Keener 1998).

Lateralization of working memory. Some WM subsystems are lateralized in PFC. One review of human WM concluded that spatial WM is more right lateralized and verbal WM left lateralized (Smith & Jonides 1997): "different neural circuits mediate verbal, spatial, and object working memory, with spatial memory being right lateralized and verbal . . . memory typically being left lateralized. The difference in lateralization is likely quantitative rather than qualitative" (p. 38). More specifically, ventral PFC dissociates by content, with verbal left and spatial right, whereas dorsal PFC typically activates bilaterally and shows only weak evidence of dissociating by content (D'Esposito et al. 1998; Smith & Jonides 1999). It is possible that PFC lateralization exists for other information processing dimensions as well.

Interactions of emotion and working memory. Hemispheric specialization for both emotion and WM separately is, by itself, hardly evidence for an interaction. However, considerable indirect evidence supports an interaction (see Heller 1990; Heller & Nitschke 1997). There are only two functional neuroimaging studies we are aware of, and both suggest that interactions might occur in areas critical for WM. Induced emotional states modulated the degree to which left PFC was activated by a verbal fluency task (Baker, Frith, & Dolan 1997). In an fMRI study described above (Gray et al. 2002) activity in lateral PFC depended conjointly on the task stimulus and the induced emotion, with the crossover pattern in activity related to behavioral performance providing strong evidence.

Summary

Approach and withdrawal emotional states might differentially modulate WM subsystems in order to differentially prioritize representations of approach and withdrawal goals, strengthening or weakening their influence over cognition and behavior. The neural system for the active maintenance and manipulation of information (WM) meets the computational requirements for both the representation of active goals and selective regulation according to the motivational class (approach, withdrawal) of the emotional states. Lateralization of goal representations would allow a separate maintenance of approach and withdrawal goals in WM subsystems, and therefore allow a relatively simple

(bottom-up) regulatory mechanism to selectively prioritize one class of goals over the other in a situationally appropriate manner.

How might the goal-regulation architecture explain the evidence for selectivity?

In this final section we speculate on how the proposed goal-regulation architecture could account for the empirical data with which this chapter began: the double dissociation between verbal and nonverbal n-back task performance revealed by induced emotion (Gray 2001) and the related effect in dorsolateral PFC brain activity (Gray et al. 2002). (Note: in this discussion, nonverbal refers only to spatial and face WM, not object WM or other modalities.) Considerably more data is needed for any interpretation of these first findings to be fully satisfactory. However, a consideration of several possibilities suggests testable hypotheses.

A conceptual comparison between the n-back task and the goal-regulation architecture is facilitated by describing both in terms of the active maintenance of context information, that is, information that constrains or otherwise biases on-going processing and behavior (Braver & Cohen 2000). In the n-back task, to comply with the instructions on a given trial, participants have to extract the relevant stimulus-based information (verbal, nonverbal) from the current percept, compare it against stimulus information held in mind from a specific previous trial, report a match or mismatch, and then update the set of stimulus items held in mind in preparation for the next trial. In the n-back task, a verbal or nonverbal stimulus serves as context information; in the goal-regulation architecture, an approach or withdrawal goal serves as context information.

In the n-back task, emotional states did not simply enhance or impair the ability to comply with task instructions, but rather had a selective effect depending on the stimulus type. Similarly, in the goal-regulation architecture, an overall or general effect (e.g., on the ability to implement any goal) would probably be deleterious. What is needed is a selective enhancement and impairment of goals depending on their motivational class (approach, withdrawal). This suggests some parallel between stimulus type in the n-back task and motivational class of goals in the goal-regulation architecture. Specifically, we posit that there exist associations between verbal and approach-related context information, and between nonverbal and withdrawal-related context information. One kind of association we consider is that of a common physiological substrate for active maintenance that is specialized by hemisphere.

In this view, approach-related states improve verbal n-back task performance because a) approach-related emotion enhances the function of a left-lateralized WM subsystem that handles the maintenance of approach-goals; and b) verbal WM depends more on that same subsystem for the active maintenance of verbal stimulus information. Withdrawal states should correspondingly impair verbal WM for dampening that subsystem (i.e., the one that is left-lateralized) in order to dampen approach goals. In contrast, to regulate withdrawal goals, approach states should impair the function of a right-lateralized substrate for the active maintenance of nonverbal information whereas withdrawal states should enhance it. That is, the association we posit is physiological: a shared substrate for the active maintenance of context information.

The hypothesis as presented so far is agnostic about whether verbal WM should be associated with approach goals and nonverbal WM with withdrawal goals. That is, the hypothesis could be the same even if lateralization was the opposite of observed (verbal right lateralized, nonverbal left lateralized). The assumption is that there are two lateralized subsystems (left, right) which support four kinds of information (approach and withdrawal goals, verbal and nonverbal information). Thus there are two possible associations: approach-verbal and withdrawal-nonverbal, or approach-nonverbal and withdrawal-verbal. The empirical pattern (left lateralization of both verbal processing and approach emotion) could be accidental.

Nonetheless, meaningful associations are also possible and potentially interesting. These would probably take the form of weak biases on computational efficiency. Having some component functions be co-lateralized so that they can be regulated by emotional states could provide a slight advantage, a positive bias in favor of such an architecture. Several such weak biases acting together could give rise to an overall and perhaps even substantial computational advantage. This argument rests on relative computational advantage, rather than computational necessity: There are considerable individual differences in the degree of lateralization, and these differences are not catastrophic.

Sustained attention might be more critical in withdrawal-related than approach-related states to facilitate temporally extended processing of a particular problem or potential threat. Nearly all creatures face the threat of predation (Lima & Dill 1990). A failure of sustained attention or vigilance in the context of a predator could be disastrous. Although sustained attention would be useful in approach-related states, it is unlikely to be as critical for approach as it is for withdrawal states. Sustained attention and attentional orienting are relatively right lateralized (Cabeza & Nyberg 2000; Pardo et al. 1991). Some evidence suggests an enhancement of sustained attention in withdrawal states:

Negative moods promote more systematic processing, whereas positive moods promote heuristic processing (see Bless & Schwarz 1999). Systematic processing probably requires more sustained attention to a problem than heuristic processing requires.

Fine versus gross movement control could be more important in approach versus withdrawal states, respectively, and there is evidence for left lateralization of fine motor control (e.g., left hemisphere control of the right hand Hellige 1993). Fine control would be more important in approach (e.g., precise grasping), whereas coordination of large muscles groups would be more critical for escape (e.g., running). Fine motor control is critical for speech production, which is one of the few functions to be completely left lateralized in almost all people (Hellige 1993).

Finally, the action of grasping an object is approach motivated. In humans, viewing objects being grasped versus viewing objects alone activates left but not right PFC (inferior frontal gyrus, BA 45) (Rizzolatti et al. 1996). In non-human primates, neurophysiological studies of grasping have revealed a class of PFC neurons, called mirror neurons, that respond to specific kinds of grasping actions regardless of whether the actions are observed or executed (Gallese & Goldman 1998). These cells are located in area F5, an analog of Broca's area in humans, crucial for language production.

In sum, a number of weak biases acting collectively could produce an overall computational advantage for co-lateralization of cognitive control functions to enable selective regulation by approach-withdrawal states. These extrapolations from the behavioral and fMRI data (Gray 2001; Gray et al. 2002) are speculative but, in principle, are empirically testable in terms of explicit computational models (e.g., Braver & Cohen 2000).

Summary

Evidence suggests that an integration of emotional state information with cognitive control can occur and comes to be represented in lateral PFC. This claim rests on evidence for selective effects of induced emotion on behavioral performance and brain activity (Gray 2001; Gray et al. 2002). How such integration comes about has not been definitively shown, although available evidence is consistent with a hemispheric basis. An integration of emotion and cognition might play an important computational role in human self-regulation. The active maintenance of goals is likely to be subserved by working memory systems. The regulation of active goals could be subserved in part by emotional states.

A mechanism for integration would allow for selective regulation that depends on emotional state, which in turn depends on appraisals or evaluations of the situation. Approach-withdrawal states could differentially modulate working memory subsystems in order to selectively prioritize entire classes of goals in a manner sensitive to on-going events. For this reason, architectures of emotional cognition that include integration could be adaptive for allowing the prioritization of goals dynamically in response to changing conditions.

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