Journal of Experimental Psychology: General
2001, Vol. 130, No. 3, 436–452

0096-3445/01/$5.00 DOI: 10.1037//0096-3445.130.3.436

Emotional Modulation of Cognitive Control: Approach–Withdrawal States Double-Dissociate Spatial From Verbal Two-Back Task Performance

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Emotional states might selectively modulate components of cognitive control. To test this hypothesis, the author randomly assigned 152 undergraduates (equal numbers of men and women) to watch short videos intended to induce emotional states (approach, neutral, or withdrawal). Each video was followed by a computerized 2-back working memory task (spatial or verbal, equated for difficulty and appearance). Spatial 2-back performance was enhanced by a withdrawal state and impaired by an approach state; the opposite pattern held for verbal performance. The double dissociation held more strongly for participants who made more errors than average across conditions. The results suggest that approach–withdrawal states can have selective influences on components of cognitive control, possibly on a hemispheric basis. They support and extend several frameworks for conceptualizing emotion–cognition interactions.

Does being "scared speechless" reveal anything about the influence of emotional states on cognition? Are there related effects on spatial processing—"giddy with joy," perhaps? Although these phenomena are quite rare, more important if less dramatic effects have been well documented. For example, actively constructing a social judgment during an emotional state increases the likelihood that the judgment will be biased, whereas judgments retrieved from memory during an emotional state are relatively immune to such distortion (Forgas, 1995). Indeed, a number of affective factors including emotional states, arousal, mood, stress, trait emotion, and emotional pathology can influence human performance on diverse cognitive tasks (e.g., Brown, Scott, Bench, & Dolan, 1994; Dalgleish & Power, 2000; Forgas, 1995; J. R. Gray, 1999; Heller, 1990; Heller & Nitschke, 1998; Humphreys & Revelle, 1984; Isen, 1993; Koelega, 1992; Oaksford, Morris, Grainger, & Williams, 1996; Revelle, 1993).

How are we to broadly integrate these results and many others? One possibility derives from the metatheoretical position that cognition and emotion both function as control systems that regulate cognition and behavior (e.g., as articulated by Braver & Cohen, 2000; Carver & Scheier, 1982, 1990; Kosslyn & Koenig, 1992; Simon, 1967). Subsystems that contribute to control and are involved in both emotion and cognition might be critical loci of interaction. The term *cognitive control* (e.g., Braver & Cohen, 2000; Posner & Snyder, 1975) refers inclusively to processes that guide or coordinate flexible information processing, especially in situations that are novel or complex. Cognitive control is not only self-regulatory but often effortful and typically intentional. Components of cognitive control include various forms of working memory, inhibition, attention, and self-monitoring. Cognitive control is not restricted to executive control processes and includes active maintenance. Many of these functions depend in part on prefrontal cortex (Fuster, 1997; Goldman-Rakic, 1987; Grafman, Holyoak, & Boller, 1995; Smith & Jonides, 1999). It is clear that some important effects of emotion are mediated by specific and relatively automatic control systems (see, e.g., LeDoux, 1996). Emotion might also modulate cognitive control in order to better coordinate overall self-regulation.

Emotional states could have nonselective effects on cognitive control. Attentional or cognitive resource models predict that emotional states of whatever type take up resources that are then no longer available for controlled cognition (e.g., Ellis & Ashbrook, 1988). Many results broadly consistent with this hypothesis have been obtained in a number of social–cognitive domains (see, e.g., Darke, 1988; Forgas, 1995). Another kind of nonselective effect is motivational: A given emotion may simply increase or decrease the willingness to engage in any effortful task, thereby influencing all forms of controlled processing in the same manner. Emotion could serve as an interrupt signal that redirects cognition to operate on a new agenda signaled by the shift in emotional–motivational state (Simon, 1967). A neurocomputational model accounts for the effects of positive affect on complex cognition (e.g., creative problem solving) in terms of slight increases in cortical dopamine (Ashby, Isen, & Turken, 1999). Although it specifies a specific neurobiological mechanism (cf. Depue & Collins, 1999), the model focuses only on positive affect. These are all important hypotheses, but they do not speak to the question of selective effects.

Emotional states might also differentially influence components of cognitive control, for example, having stronger effects on some controlled processes than others; they may even have opposite effects. Two neuropsychological accounts predict such selective effects (Heller, 1990; Tomarken & Keener, 1998), as described

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The work reported here was carried out as part of my doctoral dissertation with Stephen M. Kosslyn, whom I thank for his support, guidance, and free rein. I also thank Todd S. Braver, Randy J. Larsen, Jerome Kagan, Daniel Simons, Richard J. McNally, Michelle Leichtman, and Ken Nakayama for their helpful comments on previous versions of this article. I thank Annya Hernandez and Tracy Thall for their superb assistance in testing some of the participants.

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below. However, a strong demonstration of selective effects of emotional states on components of cognitive control is lacking. The nonselective hypotheses above could be easily extended to incorporate selective effects. Selectivity could result from different pools of cognitive resources, for example, for spatial versus nonspatial information (Baddeley & Hitch, 1974) or for each cerebral hemisphere (Boles & Law, 1998).

The aim of this study was to test a key prediction of the idea that emotional states can modulate components of cognitive control selectively and adaptively, such that some are enhanced and others impaired according to the demands of the emotional state (cf. Heller & Nitschke, 1998; Kosslyn & Koenig, 1995; Tomarken & Keener, 1998). For example, behavioral inhibition might be more important during conditions of potential threat (which produce withdrawal-related emotional states) but nonessential or even deleterious during reward seeking (approach-related states). Emotional states have selective effects on neural activity (on a hemispheric basis, Davidson, 1995; Fox, 1991; J. R. Gray, in press; Heller & Nitschke, 1997) and facial expression (Ekman & Freisen, 1978). Selectivity is not a trivial finding, however (e.g., it is surprisingly elusive using autonomic measures, Cacioppo, Klein, Berntson, & Hatfield, 1993). Thus, it is possible without being obviously the case that cognitive control functions might be selectively modulated by emotional states (Heller & Nitschke, 1998; Tomarken & Keener, 1998). Modulation on a hemispheric basis would be one way to achieve selectivity (Heller & Nitschke, 1998; Tomarken & Keener, 1998). Functions modulated by emotional states might include, for example, the active maintenance and prioritization of approach versus withdrawal goals (cf. Tomarken & Keener, 1998); attention to novel versus familiar information; sequencing, initiation, and inhibitory control of cognition and action; and fine versus gross motor control. Hemispheric differences have been suggested for a number of these functions (see Banich, 1997; Goldberg, Podell, & Lovell, 1994; Hellige, 1993; Smith & Jonides, 1999).

However, before it is worth trying to argue for a detailed, psychologically adaptive account of an emotional modulation of cognitive control, direct evidence that emotional states are able to have selective effects is needed. Selectivity is a critical first prediction of this account, and it has not been demonstrated in previous work. In the rest of the article, I present the current account in slightly more detail, followed by three experiments that tested for and support selective influences.

Toward a Prototheory

The point of this section is to raise a logical possibility: that approach and withdrawal emotional states selectively modulate cognitive control functions to coordinate and prioritize among high-level (cognitive) self-regulatory functions. Although the account as presented here is speculative and clearly raises far more questions than it answers, it leads to a more definite specification of the problem, provides a framework for theoretical investigation, and makes numerous predictions, the most critical of which was tested.

A number of effects of emotion on cognition can be categorized in part given some knowledge of the mediating neural systems on a regional basis: as anterior or posterior within the left or right hemisphere (Heller, 1990; Heller & Nitschke, 1997). Empirically, subjectively pleasant (positively valenced) emotion tends to facilitate performance on tasks that depend more on the left prefrontal cortex (PFC), whereas subjectively unpleasant (negatively valenced) emotion tends to facilitate performance on tasks dependent on right PFC (Heller & Nitschke, 1997). This framework is more nuanced than presented here and serves well to organize the extant literature (Heller & Nitschke, 1997, 1998). Many of the data come from tasks that are good for localizing brain damage on a regional basis (e.g., see Bartolic, Basso, Schefft, Glauser, & Titanic-Shefft, 1999). However, many of these tasks are not well-characterized in terms of basic information processing (Heller & Nitschke, 1997), which reduces the confidence one can place in further interpretation of the data, such as between-task comparisons.

Another perspective (Tomarken & Keener, 1998) is that approach- or withdrawal-related emotions bias the ability of prefrontal cortex to organize behavior over time (Fuster, 1997). The general idea that emotion helps mediate priorities is widely held (see, e.g., Ekman & Davidson, 1994; J. A. Gray, 1990; Lang, 1995; Lazarus, 1991; Schwarz, 1990; Simon, 1967). Tomarken and Keener's hypothesis, which is more detailed than presented here, is relatively specific about the kinds of emotion (approach, withdrawal) and kinds of psychological functions to be prioritized (those proposed by Fuster, 1997, as the functions of prefrontal cortex). These general functions include maintaining the continuity of motivation (including prospective and retrospective memory), the suppression of interference, and the shifting of strategy. Tomarken and Keener's hypothesis is exciting, and their review of evidence suggesting that depression can be understood as a failure of suppression of interference is supportive.

To make this quite general conception of cognition–emotion relationships more concrete, consider the example of goal regulation (see also J. R. Gray & Braver, in press). Goals can be considered representations that help control behavior and bias how other information is processed (e.g., Braver & Cohen, 2000). Because they are potentially powerful, they must also be regulated when circumstances change and they would do more harm than good: What is beneficial in one circumstance can have dire consequences in another (J. R. Gray, 1999). An information-processing system able to benefit from having goals would need not only a way to maintain them actively but also a way to modulate their influence when situationally inappropriate. These considerations suggest that a goal management system needs to incorporate mechanisms for both active maintenance and selective regulation. Working memory (Baddeley & Hitch, 1974) is well suited to provide active maintenance of goals or other information that act as top-down constraints on cognition and behavior (Braver & Cohen, 2000). Emotional states are well suited for regulation, as dampening or enhancing goals in a way that is consistent with ongoing circumstances as they interact with motivation. One could implement the active maintenance of goals by having hemispheric specialization for approach goals (left) and withdrawal goals (right) (Tomarken & Keener, 1998) to make regulation by emotional states as simple as possible (e.g., through neuromodulators, see General Discussion). These basic considerations hint at the possibility of complementary roles of working memory and emotion in managing goals effectively: Working memory could maintain active goals, and emotional states could regulate active goals on the basis of circumstances, selectively prioritizing approach or withdrawal goals.

Other examples of functions that might benefit from selective modulation on a hemispheric basis could be given, but far more conceptual background than can be presented here would be needed to progress from examples to theory (including computational and neurobiological considerations, see Ashby et al., 1999; J. R. Gray & Braver, in press). Nonetheless, it is a logical possibility that selective effects of emotion on cognitive control could play a functional role in high-level self-regulation.

For further progress, a first need is empirical: evidence for (or against) selective effects of emotional states on components of cognitive control. The prediction of the current account is that approach and withdrawal emotional states can enhance or impair performance depending on the particular emotion and cognitive control function involved, and that different emotional states can have opposite effects. Evidence for such a double dissociation would argue strongly for a selective effect. Although not a strict requirement, differences should be shown ideally on tasks that are as simple as possible and potentially related to hemispheric differences. Neuropsychological tasks, reasoning, and creative problem-solving tasks tend to be too complex for drawing inferences about elementary functions because such tasks permit numerous strategies, such as recoding of verbal material into spatial terms, and potentially draw on a great many abilities (imagery, memory, and so on).

A second need is theoretical: a conceptual basis for selective effects that goes beyond mere logical possibility of the type discussed above. This is by far the more daunting task, in part because there is little empirical constraint. Extant evidence tends to be neurobiological, for example, related to hemispheric differences (J. R. Gray, in press; Heller, 1990; Heller & Nitschke, 1998; Tomarken & Keener, 1998) or dopamine systems (Ashby et al., 1999), and so only indirectly informs hypotheses about psychological function. Moreover, there are a number of complex issues involved in understanding hemispheric differences in emotion and cognition (Davidson, 1992; J. R. Gray, in press; Hellige, 1993) and of relating classes of emotion to neurotransmitter systems (Panksepp, 1998). Notwithstanding the difficulties, the current conception makes a clear-cut prediction that can be rigorously tested: Selective effects of emotional states on cognitive control should be possible. If substantiated, this would make theory development more attractive as an enterprise.

Rationale of the General Method

If induced emotional states can reveal a double dissociation between two cognitive control functions, it would be strong evidence for selective effects of emotion on cognitive control. Such a dissociation would be still more meaningful if the tasks and types of emotional states are themselves relatively well understood. I therefore used spatial and verbal working memory tasks and approach–withdrawal emotion. These tasks and emotions would hint at a hemispheric basis for the dissociation, although this was not tested.

Spatial–Verbal Working Memory

Working memory refers to the system for the short-term, active maintenance and manipulation of information in the range of seconds (Baddeley & Hitch, 1974). Working memory is a natural choice for a cognitive control function here because of its importance in cognition and the diversity of efforts to specify its component processes (e.g., Baddeley, 1996; Owen, Evans, & Petrides, 1996; Smith & Jonides, 1999; Smith, Jonides, Marshuetz, & Koeppe, 1998; Waltz et al., 1999). Most relevant for present purposes, it has spatial and verbal subsystems (Baddeley & Hitch, 1974), as shown by behavioral challenge and brain damage (see Baddeley, 1986), functional neuroimaging (see D'Esposito et al., 1998; Smith & Jonides, 1999), and individual differences (Shah & Miyake, 1996). Moreover, considerable functional neuroimaging evidence suggests that some components of working memory are specialized by hemisphere, with verbal active maintenance left lateralized and spatial active maintenance right lateralized in inferior frontal gyrus (D'Esposito et al., 1998; Smith & Jonides, 1999).

Distinguishing among working memory, attention, and other aspects of cognitive control is challenging conceptually and empirically (see Braver & Cohen, 2000; Miyake & Shah, 1999). Baddeley (1986) drew on a model of attention (Norman & Shallice, 1986) to describe the central executive component of working memory. Moreover, various theorists use the same term with different emphases. Fortunately, the difficulty in demarcating various aspects of cognitive control is not critical for present purposes. The spatial–verbal distinction is conceptually clear and one of the most robust empirical results in the human working memory literature. Moreover, spatial and verbal tasks can be designed that are well matched psychometrically. Identifying which more specific aspects of cognitive control are influenced by emotion will clearly be important in further research.

Approach–Withdrawal Emotional States

Approach versus withdrawal emotion (Davidson, 1995; Fox, 1991) is one of the conceptually clearest and best validated distinctions between functional classes of experienced emotion. Considerable evidence suggests hemispheric specialization for anterior areas, although exceptions exist (J. R. Gray, in press; Heller & Nitschke, 1998). Approach states lead to greater left hemisphere activation, whereas withdrawal states lead to greater right hemisphere activation (see Davidson, 1995; Heller, Nitschke, & Miller, 1998; J. R. Gray, in press; Sutton & Davidson, 1997). The asymmetry concerns subjectively experienced emotion, and not the perception of emotion in others nor the production of emotion (which are typically right lateralized; Adolphs, Damasio, Tranel, & Damasio, 1996; Borod, Koff, Perlman Lorch, & Nicholas, 1986; Heller et al., 1998). The emphases on both function and hemispheric specialization are not essential but could be useful in developing a theoretical account. Subjective valence (e.g., positive or negative) is not directly functional (but see Carver & Scheier, 1990), and so a theoretical role is less clear than for states defined in terms of motivation (approach or withdrawal).

The approach–withdrawal distinction is concerned with goal-directed emotions and not postgoal attainment (or nonattainment) emotions (Davidson, 1998). For example, some emotions that are subjectively pleasant or positive, such as satiation, are not approach related, and some that are subjectively negative, such as disappointment, are not withdrawal related. The approach–withdrawal distinction draws empirical support from clinical populations with emotional pathology (Heller & Nitschke, 1998); electroencephalography (EEG) in neonates (Fox & Davidson, 1986), 10-month old infants (Davidson & Fox, 1982), normal adults, and adult clinical populations (see Davidson, 1995); and EEG in rhesus monkeys (Davidson, Kalin, & Shelton, 1992; Kalin, Larson, Shelton, & Davidson, 1998). Although functional neuroimaging results have been mixed (Canli, 1999), the asymmetry is found when individual differences in arousal are controlled (Canli, Desmond, Zhao, Glover, & Gabrieli, 1998).

People differ in how sensitive they are to cues of reward (approach motivation) and cues of threat (withdrawal motivation) (see Larsen & Ketalaar, 1991, for review and evidence). Some people react strongly to a given motivating stimulus (reward or threat), whereas others react little if at all. Personality measures have been developed (Carver & White, 1994) that assess trait sensitivity to cues of threat (i.e., individual differences in a hypothetical behavioral inhibition system, BIS) and trait sensitivity to cues of reward (individual differences in a behavioral activation system, BAS), based on J. A. Gray's (1970, 1982) model of personality. BIS and BAS are orthogonal dimensions; one is not predictive of the other. Asymmetry in anterior brain activity correlates significantly with the BIS–BAS measures (Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997).

Individual differences in trait emotion suggest a methodological advantage to focusing on approach–withdrawal emotion. To foreshadow the method, the BIS–BAS scales can be used to predict which individuals should experience stronger emotional states and therefore show larger effects of those states on cognitive control. Any given emotion induction is not likely to induce purely approach or withdrawal emotion (if such states exist), almost certainly not across all participants. However, individuals who are more reactive should be more affected. Their trait emotional reactivity to cues of reward or threat should selectively amplify the degree to which a given emotion induction induces an approach- or withdrawal-related state. If an effect of emotion on cognition depends specifically on approach–withdrawal emotion, then trait differences in approach–withdrawal emotion should predict the magnitude of the effect, mediated by the strength of induced emotional state.

Previous Work

Previous work hints at a dissociation between spatial and verbal working memory during approach–withdrawal emotional states but has not tested for it directly and is methodologically compromised for answering the question. In a recent review (J. R. Gray, 2001), 11 experiments suggested a dissociation between spatial and verbal working memory performance during emotional states consistent with Heller's regional framework (e.g., Heller & Nitschke, 1997). Two experiments were not consistent. However, no studies specifically contrasted spatial with verbal working memory on tasks matched for difficulty using objective measures, and so motivation or task difficulty may have confounded the results. Moreover, no studies focused on approach–withdrawal emotion specifically. Thus the extant literature (see J. R. Gray, 2001; Heller & Nitschke, 1997, 1998) hints at selective effects of emotion on spatial and verbal working memory, but focused empirical tests are lacking.

In sum, using induced emotion to dissociate spatial from verbal two-back performance is a test case of a potentially quite general, mechanistic inquiry into how normal emotional states influence cognitive control. A double dissociation would be strong evidence that emotion can have selective influences. Thus in three behavioral experiments, I sought to dissociate spatial from verbal working memory, operationalized in terms of performance on two-back tasks. I did not test which components of cognitive control necessary for two-back performance were more influenced, nor did I test whether hemispheric specialization is the basis for the interaction.

General Method

Participants in all experiments (N = 152) were right-handed Harvard University undergraduates, age range 18–27 (M = 19.4 years). They gave informed consent and were paid for their participation. None participated more than once. Equal numbers of men and women participated, and all were randomly assigned to groups within the constraints of counterbalancing.

Procedure

The key aspect of the protocol was for each participant to watch a short video intended to induce an emotional state and then to perform 100 trials of a computerized two-back task.

Emotion induction. Two sets of three 9–10 min video clips were used to induce emotional states. Each set had an approach, a neutral, and a withdrawal video. Set 1 consisted of excerpts from the video compilation *Candid Camera* (Funt, 1985), the Australian travelogue *G'Day Australia* (Queensland Tourist and Travel Corporation, 1987), and the film *Halloween* (Carpenter, Yablans, & Hill, 1978), respectively. Set 2 had excerpts from the video compilation *Best of America's Funniest Home Videos* (Vin Di Bona Productions, 1990), the film *Roger and Me* (Moore, 1989), and the film *Scream* (Craven, 1996), respectively.

To verify the emotion induction, I asked most of the participants to give self-report emotion ratings immediately before and after each video (n = 140). I unobtrusively noted behavioral reactions (e.g., overt startle, laughing) for 128 participants. Finally, in Experiment 3, I explicitly tested the prediction that individuals more sensitive to cues of threat would show larger effects of the withdrawal videos but not the approach videos, whereas individuals more sensitive to reward would show larger effects of the approach videos but not the withdrawal videos.

Two-back tasks. For the cognitive control task, a variant of the Continuous Performance Task (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) was selected on methodological grounds. In the two-back task (Braver et al., 1997), participants view a series of items (e.g., letters appearing in locations) and are instructed to indicate, for each item, whether the current item matches the one seen two trials previously. The two-back tasks have several strengths for present purposes. First, they are relatively well understood. Based on a conceptual analysis with converging evidence from patterns of brain activation, Jonides et al. (1997) described the two-back task as requiring seven elementary operations (p. 471): encoding, storage, rehearsal, matching (of current to stored), temporal ordering (to identify which item was two previous), inhibition (of currently irrelevant items), and response execution. Second, the spatial and nonspatial versions can have exactly the same visual appearance and response demands; the instructions vary, not the stimuli or mode of responding. Third, the tasks strongly constrain how people typically engage them. Given the time constraints of 3 s per trial, recoding of spatial information into verbal terms (or vice versa) is generally more difficult than doing the task as intended. Although recoding is still possible, it would work against showing a differential influence of emotion on task performance.

Each participant is instructed to press one of two computer keys on each trial to indicate whether the item on the current trial matches the item shown two trials ago (same, press the *S* key) or not (different, press the *D* key). Reaction time (RT) and accuracy are recorded for each trial, and there are 100 trials per session (i.e., following each video). RT on target trials in which a correct response is made contributes to the measure of average RT for that session, as assessing processing speed when RT is the least likely to be contaminated by spurious influences (e.g., guessing).

Pilot work established display parameters at which spatial and verbal versions were well matched for difficulty at a group level for errors and RT. Participants in the experiments reported here also found the tasks to be of equal difficulty.

The task has 10 letters (b, c, d, f, g, h, j, k, l, m) presented one per trial using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). The letters appear in black against a white background. Multiple copies of the letter for a given trial are shown in 48 point Geneva font inside a 5.4-cm square, with the 17-in. monitor resolution set at 832 × 624 pixels. The square can appear in one of six possible locations around the center of the screen (roughly following an iso-acuity ellipse: minor axis = 5.8 cm between square centers on the vertical, major axis = 7.2 cm horizontal). Each square with letters is shown for 500 ms against a background of jumbled letters, followed by a 2,500 ms period of the background alone.

The spatial instructions are to press *S* or *D* depending only on the location of the box on the screen, ignoring the identity of the letter. The verbal instructions are to press *S* or *D* depending on the identity of the letter inside the box, ignoring the location. Of the trials, 30% are targets (*S*) and 70% are nontargets (*D*), with no more than two targets in a row. Each item (letter or position) occurs as a target equally often, appears as a nontarget as close to equally often as possible, and is otherwise presented at random. The same sequence of letters-in-locations was used for the spatial and verbal versions. To ensure a uniform pace of the task, if the participant does not respond within 3 s (500 ms for the stimulus, plus 2,500 ms for the background), the task progresses with no delay to the next trial. An omission is recorded and scored as an error.

Each participant was given explicit instruction about the task, both on the computer screen and orally by the experimenter during a brief familiarization session. Instruction and 12 trials (repeated if necessary) were given prior to any video to eliminate confusion the participants may have had about the task. The familiarization session was intended to enable participants to proceed as quickly as possible from the end of the video to engaging in the task, but without becoming practiced at the task.

Analyses

Individual differences in working memory capacity are thought to reflect differences in controlled processing (see Engle, Kane, & Tuholski, 1999). In pilot work, substantial individual variation in two-back performance was found. In the work reported here, analyses were performed to both control for and capitalize on these individual differences. Participants were divided into two groups on the basis of performance: above average (low-error group) and below average (high-error group). Although the tasks were the same across participants, the degree of controlled processing required depends in part on the individual. If the predicted Emotion × Task interaction is specific to cognitive control, it should be greatest in magnitude for those performing below average.

Two examples may help make this part of the design more clear. First, in child development, a given task imposes different cognitive demands at different ages. Tasks appropriate for studying executive function at one age are often inappropriate at an older age, because they often no longer tax executive function (see Barkley, 1997; Diamond, 1990). That is, individuals can differ in executive abilities (here as a function of age), and so the same task can impose different demands on executive function. Second, when adults are acquiring cognitive skills, more effort and controlled attention are required initially than subsequently during skilled or practiced performance (Raichle et al., 1994). That is, individuals can differ in ability (here as a function of practice), and so the same task can impose a different demand. For both age and practice, the cognitive control required depends in part on the individual and situation, not the task alone. Thus if the effect of emotion is specific to controlled processing, it should be stronger in *individuals finding the two-back tasks more challenging.*

For all statistical tests, alpha was set to .05; *p* values are two-tailed.

Experiment 1

Experiment 1 tested the key prediction that spatial and verbal controlled processing would be influenced selectively by approach and withdrawal emotional states. As suggested by reviews of the extant literature (J. R. Gray, 2001; Heller & Nitschke, 1998), spatial two-back performance should be better in a withdrawal state than an approach state, whereas the opposite should hold for verbal two-back performance.

Method

The participants ($N = 24$), two-back tasks, and videos were as described in the general method. Only the first set of videos was used.

For half of the participants, self-report ratings were collected before and after each video to assess emotional state. Omitting the ratings for the participants was intended to make the time between the end of the video and the beginning of the two-back task as short as possible, so that the likely transient effects of emotion would be stronger. Self-focused attention to an emotional state while giving the ratings could also dampen the emotion. For those giving ratings, each video was preceded and followed by the emotion self-report ratings. The instructions were to indicate how strongly each of eight emotion terms (*bored, sad, energetic, amused, calm, angry, happy,* and *anxious*) described the current emotional state. Participants indicated this by making a mark on a 10-cm horizontal line provided for each term to indicate the current level, which was subsequently scored in millimeters from 0 (*not at all*) to 100 (*extremely*) (Bond & Lader, 1974). The target terms were *amused, anxious, calm, energetic,* and *bored,* taken as indexes of approach emotion, withdrawal emotion, low arousal, high arousal, and low interest, respectively.

The factors counterbalanced between subjects were gender, two-back task (spatial or verbal), video order (withdrawal–neutral–approach, neutral–approach–withdrawal, or approach–withdrawal–neutral), and ratings (collected or not collected). Each participant performed only the spatial version or only the verbal version and did so three times following each of the three videos.

Two performance groups (high error and low error) were defined on the basis of a mean split of errors averaged across all 3 two-back sessions.

Results

For all participants the crossover interaction was in the predicted direction, albeit not significantly; for the high-error group it was significantly so. The reliability of the pattern across the condition means, which are summarized in Table 1, was tested using Contrast 1 (details in Table 1). The contrast supported the prediction in the high-error group for errors, $t(14) = 2.21$, $p = .044$, with no speed–accuracy trade-off. It was not present in the low-error group, $t(26) = 0.17$, $p = .87$. The Emotion × Task interaction should have emerged more strongly in the high-error group if it is specific to cognitive control, and the results were consistent with this prediction.

The data can also be examined in terms of a relative effect, using difference scores to collapse the repeated measures. The withdrawal-minus-approach differences in RT and errors were the dependent measures, shown in Figure 1. (To allow focus on the key interaction, I do not include two-back performance after the neutral video here; it is not necessary for showing the dissociation.) In an analysis of variance (ANOVA) (task and performance groups between subjects), the effect of spatial–verbal task on the

Table 1
Contrast 1 and Two-Back Performance, Experiment 1

Group	Spatial			Verbal			MSE
	Withdrawal	Neutral	Approach	Withdrawal	Neutral	Approach	
Contrast 1	−1	0	+1	+1	0	−1	
All participants							
RT	933	919	970	971	960	942	12,391
Errors	7.1	8.8	9.8	6.9	7.5	7.0	9.44
High error							
RT	897	893	930	993	983	924	16,500
Errors	12.6	13.6	16.6	14.5	12.0	11.7	8.48

Note. Mean reaction time (RT) (ms) and errors (%) are given for the 3 (video, within subject) × 2 (task, between subjects) conditions, with *MSE*s from repeated measures analyses of variance, for all participants ($N = 24$, $df = 44$) and the high-error group ($n = 9$, $df = 14$).

withdrawal–approach difference scores is equivalent to an Emotion × Task interaction. Across all participants, this Emotion × Task effect was upheld significantly for errors, $F(1, 20) = 4.69$, $p = .042$, with no speed–accuracy tradeoff. It was also significant within the high-error group alone, $F(1, 7) = 7.03$, $p = .033$, but not within the low-error group alone, $F(1, 13) = 0.03$, $p = .86$, consistent with the contrast analyses. In a test of the difference between the high-error and low-error groups, the Performance Group × Video valence × Task interaction was marginal, $F(1, 20) = 3.80$, $p = .065$, in the direction expected (a larger Emotion × Task interaction within the high-error group than the low-error group); for RT, this interaction was in the same direction.

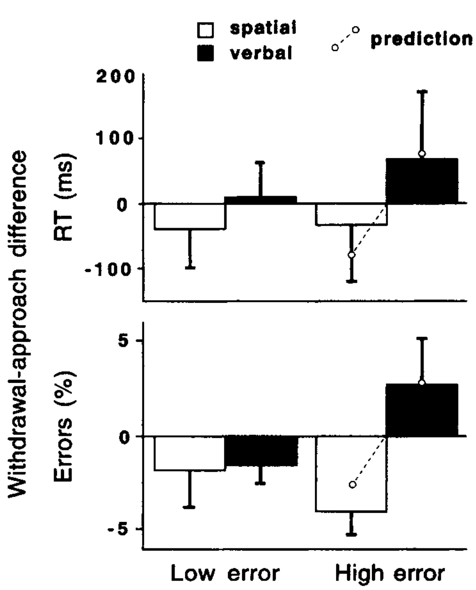

Figure 1. Spatial and verbal two-back performance, Experiment 1. The dependent variable is a difference score: mean (+ *SE*) reaction time (RT) and errors after the withdrawal video minus after the approach video, shown separately for the high-error and low-error groups. A positive value means performance for that group was worse after the withdrawal video.

Control Analyses

Task difficulty. The spatial and verbal tasks were well matched. Average errors and RT over all three video conditions were taken as the summary measures of difficulty. Potential spatial–verbal differences were tested with mixed-model ANOVAs (spatial–verbal task between subjects, videos within subject). There were no reliable differences between the tasks for errors or RT (all $ps > .50$).

Emotion manipulation. The videos induced the intended emotional states, judged on the basis of self-reported changes in emotion, summarized in Table 2. *Anxiety* (withdrawal) ratings were higher after the withdrawal video but not after the approach video. *Amused* (approach) ratings were higher after the approach video but not after the withdrawal video. Of note, there were no differences in either *calm* or *energetic* (low or high arousal, respectively) between the two emotional videos, *calm*, $F(1, 11) = 0.45$, *energetic*, $F(1, 11) = 0.01$, $ps > .5$, suggesting equal arousal despite opposite valence. The scores for *bored* (low interest) were significantly and similarly decreased (i.e., less bored) for both emotional videos but unchanged for the neutral video, suggesting heightened interest in the emotion conditions.

Other. The Emotion × Task interaction of the participants giving ratings did not differ from that of the participants who did

Table 2
Self-Reported Emotion Ratings, Experiment 1

Term	Video		
	Approach	Withdrawal	Neutral
Amused (approach)	+24.5		
Anxious (withdrawal)		+24.3	
Bored (low interest)	−20.2	−20.3	
Calm (low arousal)			+20.3
Energetic (high arousal)			−14.9

Note. Emotion ratings are mean change scores, postvideo minus prevideo (possible range = −100 to +100), shown if $p < .05$ from a paired t test against zero (no change). A positive change score indicates an increase after watching the video (e.g., more anxious after the withdrawal video than before it).

give ratings. In a mixed-model ANOVA (task, performance group, and ratings between subjects, video valence within subject), the effect of ratings was not reliable, $F(1, 16) = 1.94$, $p = .18$. Nonetheless, the effect size of the Emotion × Task interaction was half the size in the group giving ratings ($r = .27$) of that in the group not giving ratings ($r = .55$).

Discussion

Spatial performance was enhanced by a withdrawal state and impaired by an approach state, whereas verbal performance was enhanced by an approach state and impaired by a withdrawal state. The double dissociation held in a direct comparison between well-matched tasks (objectively equated for difficulty, identical in appearance). For participants making more errors than average, the crossover interaction held in absolute terms. Thus the experiment provides evidence that components of cognitive control can be dissociated by induced emotional states.

Because the Emotion × Task interaction was a double dissociation, the plausibility of a number of alternative accounts is greatly reduced. Motivational differences between the emotion conditions are not plausible on this basis. The effect is not attributable to differential arousal, given the self-report ratings showing similar levels of arousal for the oppositely valenced emotion inductions. The double dissociation also means that an arousing but emotionally neutral condition was not required in the design.

The neutral condition is not required to show the dissociation, yet it is additionally informative. In particular, there was no main effect of the neutral versus emotion conditions; neutral performance was typically intermediate. This means that the double dissociation—itself a strong result—is even more straightforward to interpret.

Experiment 2

A first aim of Experiment 2 was to replicate the findings of Experiment 1 in a large sample.[1] A second aim was to establish that the key effect depends on approach and withdrawal emotion rather than on some other aspect of the videos. These data are presented as Experiment 3 for greater continuity.

Method

The participants ($N = 128$) and tasks were as described in the General Method. Each participant filled out a consent form and the State–Trait Anxiety Inventory (STAI; Spielberger, 1977), Form Y. Each participant then had the familiarization trials, and four repetitions of video plus task. Each video was preceded and followed by a brief emotion rating scale, followed by a two-back task. After the last two-back task and a final emotion rating, participants completed the BIS–BAS scale (Carver & White, 1994) and the Eysenck Personality Questionnaire—Revised (EPQ–R; S. B. G. Eysenck, Eysenck, & Barrett, 1985), short form. They were debriefed and paid for their participation.

The measures of self-reported emotional state were obtained in part to validate the emotion induction and in part to pilot test items for a rating scale sensitive to approach–withdrawal emotional states. These data were collected using a procedure very similar to that described in Experiment 1, with 11 terms per scale. Only the data for the terms *amused* (approach), *anxious* (withdrawal), and *content* are reported here.

Each participant saw four videos, two emotional and two neutral, to allow within-subject comparisons of the influence of an emotion condition against a neutral condition for both spatial and verbal tasks. The within-subject factors were task (spatial or verbal) crossed by video type (emotional or neutral). For half of the participants, the two emotional videos were the withdrawal videos; for the other half they were the approach videos. All participants saw the two neutral videos.

The between-subjects factors were gender, valence of the emotional video (approach or withdrawal), video order (emotional–neutral–neutral–emotional or neutral–emotional–emotional–neutral), task order (spatial–spatial–verbal–verbal or verbal–verbal–spatial–spatial), and video version order (Set 1–Set 1–Set 2–Set 2 or Set 2–Set 2–Set 1–Set 1). Thus there were 32 cells, with 4 participants per cell. Random assignment was done within blocks of 32 (i.e., the first 32 participants were tested before the next 32 were begun).

A mean split on percentage of errors across all two-back sessions was used to define two performance groups (high-error or low-error).

Results

The data are shown in Figure 2 and summarized in Table 3. For RT, as tested by Contrast 1 (see Table 1), the crossover interaction was reliably present across all participants (effect size $r = .24$). This pattern held more strongly within the high-error group ($r = .32$) and less strongly within the low-error group ($r = .15$). For errors, the same trend was present, that is, there was no speed–accuracy tradeoff across all participants or within the high-error group. (There was a tradeoff in the low-error group, which compromises interpretation of their performance in isolation. Interpretation of the data from all participants, the high-error group alone, and the high- vs. low-error groups is not compromised.)

Note that Contrast 1 does not recapitulate the experimental design (factorial, repeated measures) in two ways. First, only the data from the first two-back session were used in this analysis. The reason is that two strong order effects (i.e., effects due to serial position within the four repeated measures) were present and would work against showing an Emotion × Task interaction. In later sessions, the emotion inductions were weaker and the tasks were more practiced ($ps < .0001$; see order effects in the *Control Analyses* section). And second, the two neutral groups were combined to give a more stable estimate of performance in the neutral condition. The reason is that the data were analyzed by focused contrast (for greater specificity) rather than factorial ANOVA (used in Experiment 3 and control analyses). The participants in the two neutral groups should not have differed during the first two-back session because their protocols diverged only on presentation of the second (nonneutral) video. This means there are unequal sample sizes per group, and the contrasts were computed accordingly (Rosenthal & Rosnow, 1985).

For errors, the effect size for the high-error group ($r = .21$) was significantly larger than the effect size for the low-error group ($r = -.26$), as tested meta-analytically, $Z = 2.59$, $p = .0096$; for RT the same trend held, albeit not significantly, $Z = 0.53$, $p = .59$. An ANOVA with high–low error group as a factor also supports this conclusion, with the data fourth-root transformed to acceptably equate the variance between groups. For errors, the 3 (video valence) × 2 (task) × 2 (performance group) interaction was

[1] The Approach–Withdrawal × Spatial–Verbal task interaction replicated in an experiment not reported here with $n = 32$ using the same tasks and videos.

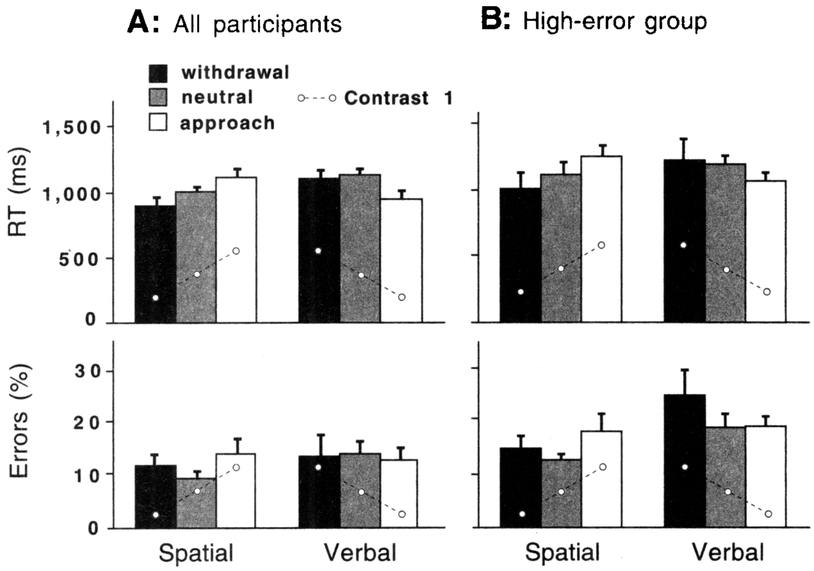

Figure 2. Spatial and verbal two-back performance by video condition, Experiment 2. Mean (+ *SE*) reaction time (RT) and errors within the 3 (video) × 2 (task) conditions, for (A) all participants (n = 128), and (B) the high-error group only (n = 46). The display does not recapitulate the experimental design (see Experiment 2, *Method* and *Results*).

significant, $F(2, 116) = 4.89, p = .0091$, in the direction expected and with no speed–accuracy tradeoff.

Control Analyses

Task difficulty. The spatial and verbal two-back tasks were well matched for these participants, as shown by a focused contrast on the data shown in Figure 2A. Using lambdas for spatial = −1, verbal = 1, there was no difference between the tasks for errors, $t(122) = 0.82, p = .41$, or for RT, $t(122) = 1.17, p = .24$. The spatial-neutral group made fewer errors (9% errors) than the verbal-neutral group (12%), which is not problematic. The neutral groups are not required for showing a double dissociation, and so the difference is of no real concern. One might think that performance in the neutral condition is somehow a better measure of task difficulty and so conclude that the tasks are not well matched. However, difficulty is not a property of a task but depends as well on both the participants and the conditions under which the task is performed (e.g., age, practice). In fact, difficulty in the neutral condition is unreliable as a guide to difficulty in the emotion conditions. As a hypothetical example, emotional arousal might somehow influence spatial and verbal tasks differentially, even if they were equated in neutral conditions. Difficulty needs to be matched in the emotion conditions, and it clearly was.

Emotion manipulation. The videos induced emotional states as intended. Six participants of 64 (9%) gasped or startled overtly at some point during both withdrawal videos (at least once per video); 37 of 64 (57%) laughed audibly at some point during both approach videos (at least once per video). No participant laughed during both withdrawal videos or startled during either approach video. The self-report ratings of emotional state differed strongly by video type and in the directions expected.[2]

Order effects. The videos were less effective at inducing emotional states if they came later in the session order, as assessed by the ratings. In three mixed-model ANOVAs (session within subject, video order between subjects), with the three dependent variables of change scores for *amused, anxious,* and *content,* there were significant effects of session for all three, $Fs(3, 372) = 16.3$, 12.4, and 3.27, with $ps < .0001$, .0001, and .02, respectively. The mean change scores for *amused, anxious,* and *content* declined monotonically over the course of the four sessions, suggesting a systematically less effective emotion induction.

Participants made the most errors on the two-back tasks in the first session. Averaging over video and task conditions, mean errors in the first session was 12%, versus 8%, 9%, and 9% in subsequent sessions. In a repeated measures ANOVA (session within subject), there was a main effect of session for errors, $F(3, 381) = 12.1$, and RT, $F(3, 381) = 36.2, ps < .0001$.

Discussion

This experiment found further evidence for a double dissociation between spatial–verbal two-back performance under induced emotional states, replicating the results of Experiment 1 in a large sample. The crossover interaction held in absolute terms across all participants. It held significantly more strongly for participants making more errors than average than for those making fewer errors, suggesting specificity to cognitive control. Those making fewer errors showed no effect and perhaps an opposite one (a speed–accuracy trade-off makes it uncertain). The counterintuitive prediction that spatial performance would be enhanced by a withdrawal state and impaired by an approach state was uniformly upheld.

[2] Change scores were computed as postvideo level minus prevideo level and used as dependent variables in ANOVAs (approach–withdrawal group between subjects). Details are available on request.

Table 3
Two-Back Performance, Experiment 2

Measure	Video: Withdrawal	Video: Neutral	Video: Approach	Contrast 1: t	Contrast 1: p	Contrast 1: r	Contrast 1: MSE
All participants							
RT				2.74	.007	.24	59,680
Spatial	913	1,011	1,099				
Verbal	1,095	1,113	975				
Errors				0.34	.74	.03	65.9
Spatial	11.5	8.6	12.4				
Verbal	12.1	12.4	11.7				
High-error group							
RT				2.16	.036	.32	65,947
Spatial	1,007	1,115	1,268				
Verbal	1,227	1,196	1,069				
Errors				1.38	.18	.21	75.8
Spatial	14.7	12.6	17.9				
Verbal	24.8	18.4	18.8				
Low-error group							
RT				1.35	.18	.15	47,382
Spatial	841	982	930				
Verbal	1,016	1,056	932				
Errors				−2.36	.021	−.26	19.5
Spatial	9.0	7.4	7.0				
Verbal	4.4	8.3	8.5				

Note. Mean reaction time (RT) (ms) and errors (%) are given for the 3 (video, between subjects) × 2 (task, between subjects) conditions, with *MSE*s from analyses of variance. Values for t, p, and effect size r are from Contrast 1, for all participants (n = 128, df = 122), the high-error group (n = 46, df = 40), and the low-error group (n = 82, df = 76). The contrast does not recapitulate the design (see Experiment 2, *Method* and *Results*).

Experiment 3

The aim of this experiment was to show that the influence of the videos on two-back performance is attributable to emotional states rather than to other correlates of watching the videos. Further, the influence of the videos should be specific to approach–withdrawal emotion.

Because well-validated, trait emotion measures are available, a strategy that capitalizes on individual variation has much to recommend it. The logic is that some participants should be more reactive to specific classes of emotional stimuli than other participants. Those most reactive should show the largest influences of the videos on spatial versus verbal performance. Using individual differences in this way gives a strong test in a large sample with well-validated measures. The videos do serve as an emotional challenge and plausibly involve some degree of approach and withdrawal emotion, as comparisons with other work suggest (Sobotka, Davidson, & Senulis, 1992; Tomarken, Davidson, & Henriques, 1990). The strength of the resulting emotional states should differ systematically across participants as a function of trait reactivity.

Trait scales that meet the present requirements are available. For approach–withdrawal, the BIS–BAS scales (Carver & White, 1994) consist of self-report questions that target sensitivity to cues of threat and cues of reward. The BIS–BAS measures correlate significantly with the prefrontal EEG asymmetry (Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997). That is, high-BIS/low-BAS individuals (high reactivity to cues of threat but not reward) have greater right hemisphere activity, and high-BAS/low-BIS individuals (high reactivity to cues of reward but not threat) have greater left activity. The other individuals (high–high, low–low) are intermediate in terms of hemispheric asymmetry. The prediction is that BIS–BAS measures should be associated with the Emotion × Task interaction, and more strongly than a comparison trait measure that is less specific at targeting approach–withdrawal reactivity. The relation should be more evident after an emotional provocation than a control (neutral) condition if these individual differences are acting as selective amplifiers of approach–withdrawal emotional states.

For a comparison trait-emotion scale, the EPQ–R (S. B. G. Eysenck et al., 1985), short form, was selected to assess Neuroticism and Extraversion. Almost all factor-analytic assessments of personality from self-report measures find dimensions associated with negative and positive emotionality (Costa & McCrae, 1980; Watson & Clark, 1984). The two factors are associated with both reactivity to affective stimuli and the level of typical affect (Costa & McCrae, 1980; Gross, Sutton, & Ketalaar, 1998; Larsen & Ketalaar, 1991). Neurotic individuals tend to experience negative affect more frequently and to react more negatively to unpleasant events. Extraverted individuals tend to experience positive affect more often and to react more positively to pleasant events. For this reason, Neuroticism and Extraversion are appropriate measures of trait emotion against which to compare the BIS–BAS measures in

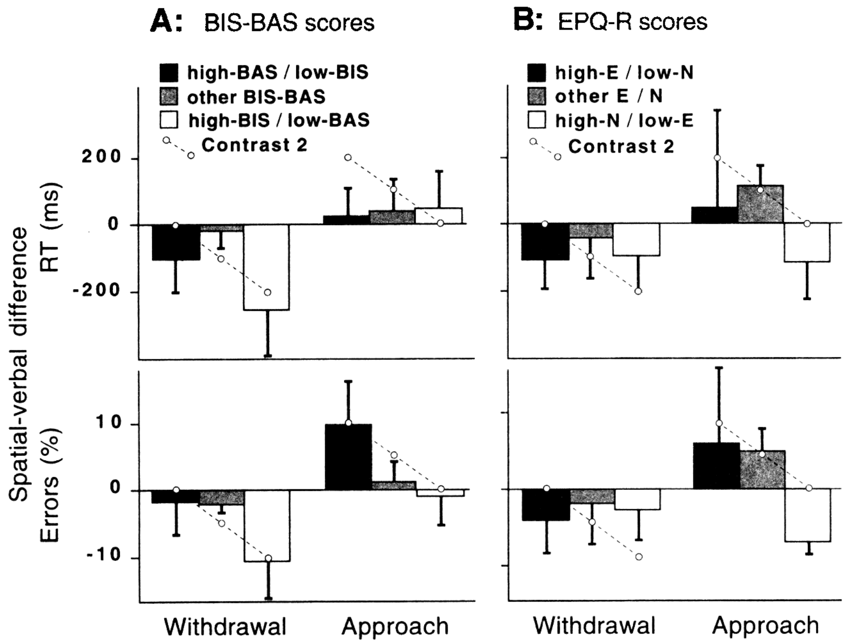

Figure 3. Spatial–verbal two-back performance by trait group, Experiment 3. Participants are classified in terms of (A) their BIS–BAS scores or (B) their EPQ–R Neuroticism (N) and Extraversion (E) scores. The dependent variable is the mean (+ *SE*) spatial–verbal difference score in the emotion condition within 3 (trait) × 2 (video) groups, shown for participants making more errors than average; see Table 5 for a summary of related analyses. A positive difference score means verbal performance was better than spatial. BIS = behavioral inhibition system; BAS = behavioral activation system; EPQ–R = Eysenck Personality Questionnaire—Revised, short form; RT = reaction time.

terms of their effectiveness at predicting the Emotion × Task interaction.

To show specificity of the effect to approach–withdrawal emotion, I contrasted the two-back performance of participants who are simultaneously above the mean on BIS and below the mean on BAS (denoted high BIS/low BAS) against those who are below the mean on BIS and above the mean on BAS (i.e., high BAS/low BIS). The prediction was that the high-BIS/low-BAS group would show the Emotion × Task interaction in response to withdrawal videos, yet not strongly in response to approach videos. Conversely, the high-BAS/low-BIS group should show the Emotion × Task interaction in response to the approach videos, yet not strongly in response to the withdrawal videos. For Neuroticism–Extraversion, which are emotion related but not as specific to approach–withdrawal emotion, there may well be an association with two-back performance, but a less specific one.

Method

All data were collected in Experiment 2. High and low trait groups were defined by mean splits on each of the four measures (BIS, BAS, Neuroticism, and Extraversion).

The specific pattern of spatial versus verbal two-back performance within trait groups was tested using a focused contrast on groups defined by trait emotion scores. Six groups were defined: 2 (video: approach or withdrawal) × 3 (trait: high BIS/low BAS, high BAS/low BIS, or other). For Neuroticism–Extraversion, the same participants were categorized instead on the basis of mean splits on the EPQ–R trait measures, as three trait groups (high neuroticism/low extraversion, high extraversion/low neuroticism, and other). The prediction was that high-BIS/low-BAS individuals would show better spatial than verbal two-back performance but only after a withdrawal video, high-BAS/low-BIS individuals would show better verbal than spatial performance but only after an approach video, and the other groups would be intermediate. This effect should be stronger after an emotion induction than after a neutral control condition.

Results

BIS–BAS. The strength of the Emotion × Task interaction found in Experiment 2 was indeed predicted by BIS–BAS scores. Errors and RT are summarized in Figure 3A as spatial–verbal difference scores within Video × Trait Groups for participants in the high-error group. The reliabilities of these associations were tested using Contrast 2, Table 4; the full set of analyses are summarized in Table 5. The pattern was reliable not only after the emotional videos (emotion-only analyses) but also when I controlled for baseline ability by subtracting each participant's neutral performance for each task (emotion–neutral analyses). The same pattern held across all participants.

Neuroticism–Extraversion. Neuroticism–extraversion groups did not show a reliable association with two-back performance. Contrast 2 was applied to the data for groups defined by High–Low Neuroticism × High–Low Extraversion, summarized in Table 5. Across all participants, the contrast was not significant for either the emotion-only or emotion-neutral comparison. Within the high-error group, the contrast was in the same direction as for BIS–BAS but not significantly so for either the emotion-only condition, shown in Figure 3B, or the emotion-neutral condition

Table 4
Contrast 2: Trait by Video Interaction, Experiment 3

Trait measure and lambda	Withdrawal			Approach		
BIS–BAS EPQ–R	High BAS/low BIS High E/low N	Other Other	High BIS/low BAS High N/low E	High BAS/low BIS High E/low N	Other Other	High BIS/low BAS High N/low E
Lambda	0	−1	−2	2	1	0

Note. A positive lambda means that the two-back spatial minus verbal difference score is predicted to be positive for errors and reaction times (i.e., verbal performance better than spatial), a negative lambda means the opposite, and a lambda of zero means little difference. BIS = behavioral inhibition system; BAS = behavioral activation system; high = above the mean on a trait measure; low = below the mean; EPQ–R = Eysenck Personality Questionnaire—Revised, short form; N = Neuroticism; E = Extraversion; other = high/high or low/low.

(Table 5). Thus Neuroticism–Extraversion scores were not reliably associated with the specific pattern, although the trends were in the same direction.

Control Analyses

Several relevant control analyses are reported in Experiment 2.

Emotional reactivity. A guiding assumption was that the high and low trait groups would respond differently to the same videos, which they did. Differences in reactivity were in the expected directions, as shown by postvideo minus prevideo change scores on the self-reported emotion measures. The mean change scores for *amused, anxious,* and *content* were submitted to ANOVAs, which mostly confirmed the selectivity in differential strength of the induced emotions. For BIS–BAS, the interactions of Video (approach, withdrawal) × Trait Group (high BIS/low BAS, high BAS/low BIS) were significant and in the direction expected for *anxious,* $F(1, 60) = 8.52, p = .0049$, and *content,* $F(1, 60) = 6.58$, $p = .013$, although not for *amused,* $F(1, 60) = 1.04, p = .31$. One possibility is that the term *amused* might not be specific to approach-related emotion. For Neuroticism–Extraversion, the Video × Trait Group interactions were in the same directions but not significantly so for *anxious,* $F(1, 69) = 1.81, p = .18$, *content,* $F(1, 69) = 0.81, p = .37$, or *amused,* $F(1, 69) = 0.73, p = .40$. Of note, the high-BIS/low-BAS participants viewing the withdrawal videos had the strongest differential reactivity (*anxiety*), and these participants showed the strongest effects on spatial–verbal two-back performance.

Trait measures. In addition to differential reactivity, trait groups should have shown different levels of ongoing affect (Gross et al., 1998), which they did. A measure of state anxiety, the STAI State Scale (STAI–S), was obtained when participants entered the laboratory before any emotion induction or task. As summarized in Table 6, BIS and Neuroticism were positively correlated with STAI–S, whereas BAS was negatively correlated with STAI–S (all $ps < .05$).

As expected from random assignment, the group seeing withdrawal videos did not differ from those seeing approach videos on BIS, BAS, Neuroticism, or Extraversion, all $Fs(1, 122) < 1.10$, $ps > .30$.

Discussion

The specificity of the Emotion × Task interaction to BIS–BAS groups was striking. After the withdrawal videos, verbal two-back performance was worse than spatial for those participants who were above the mean on BIS and below the mean on BAS. The opposite held for those above the mean on BAS and below the mean on BIS, with others intermediate. Thus, BIS–BAS scores were significantly and specifically associated with differential spatial–verbal two-back performance after the emotion induction. The relation is a stronger result than simply an association with

Table 5
BIS–BAS Scores Predict the Emotion × Task Interaction, Experiment 3

	BIS–BAS				Neuroticism–Extraversion			
	High error		All		High error		All	
Measure and emotion condition	$t(40)$	p	$t(122)$	p	$t(40)$	p	$t(122)$	p
Errors								
Emotion only	2.95[a]	.005	2.19	.03	1.44[a]		0.80	
Emotion − neutral	3.02	.004	1.31		0.73		0.07	
Reaction time								
Emotion only	2.07[a]	.04	−0.64		1.19[a]		0.14	
Emotion − neutral	1.77		0.03		0.59		0.63	

Note. A positive *t* value indicates that the predicted direction of spatial–verbal two-back performance within emotion conditions (emotion only or emotion minus neutral) was upheld as assessed by Contrast 2 (see Table 4). BIS = behavioral inhibition system; BAS = behavioral activation system.
[a] The corresponding data are shown in Figure 3.

Table 6
Self-Reported Trait Emotion, Experiment 3

				Simple correlations (r)			
Trait measure	Range	M	SD	BIS	BAS	Neuroticism	Extraversion
BIS	11–28	20.54	4.03	—			
BAS	29–52	41.90	5.14	−.04	—		
Neuroticism	0–12	5.12	3.34	.64	−.06	—	
Extraversion	0–12	8.11	3.06	−.05	.34	−.18	—
STAI–S	20–67	33.1	9.34	.21	−.18	.35	−.14
STAI–T	21–68	36.4	9.10	.45	−.25	.66	−.26

Note. $N = 128$. If $|r| > .174$, $p < .05$. STAI–S = State–Trait Anxiety Inventory—State scale; STAI–T = State–Trait Anxiety Inventory—Trait scale; BIS = behavioral inhibition system; BAS = behavioral activation system.

trait measures, because it was not explained by differential ability at baseline. This was shown within subject by subtracting neutral performance, removing performance differences attributable to not only traits but also gender, and so on. Thus the results strongly suggest specificity to emotional states.

The relation did not hold as well for Neuroticism–Extraversion, and there are at least two interpretations. The BIS–BAS scales could simply be more accurate measures of the same underlying traits (for evidence, see Rusting & Larsen, 1999). Conversely, it could be argued that the BIS–BAS dimensions are in the same space as Neuroticism–Extraversion but rotated within it and so measure essentially two different aspects of personality (J. A. Gray, 1994). Under either interpretation, the specificity to BIS–BAS was gratifying.

General Discussion

Performance on psychometrically matched spatial and verbal two-back tasks was influenced oppositely by induced approach and withdrawal emotional states. The overall pattern was that an approach state tended to impair spatial performance and improve verbal, whereas a withdrawal state tended to improve spatial performance and impair verbal. The double dissociation is strong evidence for a selective effect of emotion on components of cognitive control. It both supports and extends current frameworks of emotion–cognition interactions (Ashby et al., 1999; Heller & Nitschke, 1997; Tomarken & Keener, 1998), at least for approach–withdrawal emotion.

Beyond simply showing a selective effect of emotion on cognitive control, the results are also consistent with a further aspect of the theoretical account: modulation on a hemispheric basis. If approach–withdrawal states modulate cognitive control functions selectively by cerebral hemisphere, then they should reveal dissociations between tasks that depend if only in part on opposite hemispheres. Considerable neuroimaging evidence suggests that the active maintenance of verbal information depends more on left PFC (Broca's area, supplementary motor and premotor areas), whereas the active maintenance of spatial information depends more on right PFC (premotor areas) (Smith & Jonides, 1999). There is also considerable evidence for hemispheric specialization in approach–withdrawal emotion (Davidson, 1995; J. R. Gray, in press; Sutton & Davidson, 1997). Modulation of cognitive control on a hemispheric basis is a parsimonious explanation for the current results, taken in the context of physiological evidence.

There are several important yet less obvious points to note about what the results do and do not show. The overall pattern was reliable across experiments as tested by focused contrasts. However, within each experiment many of the possible tests of pairwise differences between the six conditions would not have been statistically reliable (in Figure 2A, the only pairwise test having $p < .05$ was verbal approach vs. withdrawal for RT). The contrasts show only that the overall pattern is reliable. Other work suggests that some of the pairwise dissociations are reliable (for reviews, see Brown et al., 1994; M. W. Eysenck, 1982; M. W. Eysenck & Calvo, 1992; J. R. Gray, 2001; Heller & Nitschke, 1997, 1998).

The most stable estimate of the effect size was $r = .24$ (Experiment 2, $n = 128$). Finding ways to make the effect larger would facilitate further investigation. The modest effect size partly reflects large individual differences in both emotional reactivity and task performance. The Emotion × Task interaction was strongest for those performing below average. Participants performing above average showed a significant effect in the opposite direction for errors, but with some speed–accuracy tradeoff. Of interest, some effects of dopaminergic drugs on cognitive control depend on individual differences in working memory capacity (Kimberg, D'Esposito, & Farah, 1997). Bromocriptine, a dopamine receptor agonist, influenced executive-task performance oppositely (a crossover interaction) for high versus low capacity individuals. This finding could be relevant here because of work suggesting a link between positive emotion and dopamine (Ashby et al., 1999; Depue & Collins, 1999). It is also possible that the participants performing better than average were able to exert compensatory control and so showed little effect of emotion on the behavioral measures. If so, they might show a cost on a secondary task.

The analyses using individual differences in two-back task performance suggest but do not unambiguously implicate working memory. The two-back tasks are widely used to activate working memory networks in neuroimaging studies and clearly tax cognitive control. Moreover, individual differences in performance on working memory tasks are thought to reflect differences in controlled processing (Engle et al., 1999). Thus the data suggest that the effect is specific to cognitive control. Although working memory is clearly a strong candidate for a more specific locus of the effect, more work is needed to establish this possibility.

A final nuance is that the emotional states appeared to bias both spatial and verbal performance away from neutral, rather than merely improving performance in what would be a hemisphere-congruent manner. If this pattern is reliable, it is potentially explicable in terms of reciprocal inhibition between approach–withdrawal systems (cf. Solomon & Corbit, 1974).

An obvious direction for future research is to investigate the effects of approach–withdrawal emotional states on other components of cognitive control. Is the effect truly specific to working memory, as suggested but not demonstrated by the two-back data? Further components include active maintenance versus executive processing (Baddeley & Hitch, 1974; D'Esposito et al., 1998; Smith & Jonides, 1999); components of executive processing, including the coordination of dual task performance, strategy switching, sequencing (temporal ordering), selective attention, and memory monitoring (Baddeley, 1996; Robbins, 1996; Shallice & Burgess, 1996); subgoal maintenance and execution (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999); sustained attention and vigilance (Pardo, Fox, & Raichle, 1991; Posner & Peterson, 1990); inhibitory control, the regulation of prepotent or dominant responses (Diamond & Goldman-Rakic, 1989; Roberts, Hager, & Heron, 1994); and intentional or "willed" action (Frith, Friston, Liddle, & Frackowiak, 1991; Hyder et al., 1997) and cognition, such as intentional memory encoding (Kelley et al., 1998).

The most simple prediction of the current account is that cognitive control functions that show hemispheric specialization in PFC will also show selective modulation by approach and withdrawal states. Functions that depend more on left PFC (e.g., sequencing) should be more accurate or faster during approach-related states than withdrawal-related states. Even if such a simple account is largely correct, it is unlikely to describe all the data. Tasks rarely target a single cognitive process, and there could be conflicting effects of emotion on different task components. Another source of complexity is that approach and withdrawal systems are not simply mirror images of each other in functional terms (see Cacioppo, Gardner, & Berntson, 1999; Miller, 1944).

Normal emotional states might have unique strengths and applications as a tool for investigating cognitive control,[3] given their strong psychological validity and potential for functionally specific influences on self-regulation. That is, just as dual task methods, brain damage, pharmacological challenge, and so on, have provided insight into cognitive control, normal emotional states might also prove useful.

An influence of cognitive control on emotion is likely, that is, a reverse effect. Effortful cognitive tasks return an induced mood to baseline, regardless of valence, whereas easy tasks do not (Erber & Tesser, 1992). It would therefore be interesting if the effectiveness of a cognitive control task at normalizing mood depended on the task and mood.

Toward a Theoretical Basis

Theorizing will need to proceed cautiously. The current results are consistent, at least, with the idea of goal-regulation as a conceptual thread running through cognition, emotion, and the functional organization of the brain. Yet an association of verbal working memory with approach emotion and spatial working memory with withdrawal emotion could be coincidental (e.g., perhaps simply an uninteresting consequence of co-lateralization). Conversely, to speculate, the spatial and verbal tasks could be interpreted as behavioral probes of prefrontal subsystems that also support the active maintenance of approach–withdrawal goals (cf. Tomarken & Keener, 1998). Under this account, approach and withdrawal states could have opposite effects on two-back performance not to regulate the active maintenance of spatial and verbal information but to regulate the systems responsible for maintaining active approach–withdrawal goals (J. R. Gray & Braver, in press). That active maintenance but not manipulation shows hemispheric specialization (Smith & Jonides, 1999) fits with cognitive considerations concerning the critical computations for goal management. It seems likely that goals would require active maintenance but not a high degree of ongoing manipulation.

Another possible reason for the empirical association of enhanced verbal two-back performance with approach-related states is that some components of cognitive control could be more important for both approach behavior and verbal working memory, and other components for withdrawal behavior and spatial working memory. For example, sequencing is plausibly required more for approach and verbal controlled processing, whereas sustained attention might be required more for withdrawal and spatial controlled processing. That neural networks for sequencing are more left lateralized (Banich, 1997; Owen, Doyon, Petrides, & Evans, 1996) and for sustained attention more right lateralized (Cabeza & Nyberg, 2000; Pardo et al., 1991) in PFC is consistent with this possibility.

Lateralization of components of cognitive control could serve as a simple way to make a physiological regulatory mechanism as easy to implement as possible. Diffuse effects that can nonetheless be segregated on a gross physical basis would have the twin advantages of being able to modulate a number of component functions at the same time (within a hemisphere), yet also be able to have specific effects (between hemispheres). To speculate, the diffuse projecting catecholamines, dopamine (DA) and norepinephrine (NE), have neuromodulatory functions plausibly suited for such a role.

DA might mediate the effects of positive emotion on cognition (see Ashby et al., 1999; Depue & Collins, 1999). Computational models can account quantitatively for the effects of DA on working memory at the level of both neural systems (Braver & Cohen, 2000) and single neurons (Durstewitz, Kelc, & Gunturkun, 1999). Conversely, NE might partially mediate some aspects of withdrawal-related emotion. For example, pharmacologic administration of NE agonists leads to increased anxiety or panic at high doses (J. A. Gray, Owen, Davis, & Tsaltas, 1983; Zuckerman, 1984), and yohimbine facilitates the acoustic startle reflex in humans (Morgan et al., 1993).

Given strong biochemical and physiological similarities between DA and NE, it is possible that they exhibit similar patterns of activation dynamics and exert similar neuromodulatory effects on cognitive control functions in PFC. NE, like DA, exerts a modulatory effect at both inhibitory and excitatory synapses and leads to phasic activity responses that are stimulus specific (Aston-Jones, Valentino, Van Bockstaele, & Meyerson, 1994; Foote, Bloom, & Aston-Jones, 1983). NE and DA systems are functionally similar at the synaptic level yet anatomically segregated, with

[3] I thank Todd S. Braver for this insight.

NE showing greater posterior and dorsal connections and DA showing greater connectivity in ventral anterior regions. It is also intriguing that NE appears more right lateralized and DA more left lateralized (for reviews see Tucker & Williamson, 1984; Wittling, 1995). The evidence for laterality could be stronger but comes from a range of both human and animal studies, involving hemispheric lesions (Robinson, Kubos, Starr, Rao, & Price, 1984), measurement of neurotransmitter metabolites under emotional conditions (Carlson, Fitzgerald, Keller, & Glick, 1991), and neural connectivity (Oke, Keller, Medford, & Adams, 1978). Finally, the NE and DA systems are mutually inhibitory within the PFC (Tassin, 1998), consistent with opponent processing in emotion (Solomon & Corbit, 1974).

Constraints on Models of PFC

Viable models of PFC must accommodate both cognitive and emotional functions within a unified, mechanistic framework (Braver & Cohen, 2000; Damasio, 1998; cf. Metcalfe & Mischel, 1999). However, there have been relatively few investigations of how emotional states modulate PFC functions, and so there are not many constraints on such accounts. The present results suggest two. First, a substrate critical for two-back performance is needed that can be influenced by approach–withdrawal emotion. Second, such a substrate must support differential effects of approach–withdrawal emotion on spatial and verbal two-back tasks. Integrating the two constraints would be facilitated by understanding more specifically the mechanisms of cognitive control that are modulated by approach–withdrawal emotion. Individual differences are likely to be important (Kimberg et al., 1997; Revelle, 1993). The neuromodulatory effects of DA on working memory are a promising avenue for integrative research.

Summary

Approach–withdrawal emotional states can double-dissociate performance on spatial and verbal two-back tasks. In other words, emotional states can selectively modulate components of cognitive control. The results support and extend several neuropsychological frameworks for cognition–emotion interactions and constrain models of PFC function.

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Received September 20, 1999
Revision received February 22, 2000
Accepted July 20, 2000 ■