Research Report

Separating Sustained From Transient Aspects of Cognitive Control During Thought Suppression

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ABSTRACT—*Cognitive theories of how people regulate their thoughts have suggested the involvement of two control processes that occur over different time courses. These cognitive accounts parallel recent neural models of executive control, which suggest that the prefrontal cortex (PFC) mediates sustained changes in the allocation of control processes, whereas the anterior cingulate cortex (ACC) relays a transient need for additional control. Combining these cognitive and neural models of control, we used recently developed analysis techniques to distinguish transient from sustained changes in brain activation while subjects attempted to suppress an unwanted thought. Results were consistent with both models: Dorsolateral PFC demonstrated sustained increases in activation during attempts at thought suppression, whereas bilateral ACC demonstrated transient increases associated with occurrences of unwanted thoughts. These data support proposals regarding the different contributions made by the PFC and ACC to executive control and provide initial neuroimaging support for dual-process models of how individuals regulate their thoughts.*

Successful negotiation of everyday life depends critically on the ability to eliminate unwanted thoughts from consciousness. Whether these thoughts are destructive behavioral impulses, derogatory beliefs about other people, or personally debilitating ruminations, a fundamental human skill is the capacity not to dwell on such information. But how exactly do people realize this objective and gain mastery over their thoughts?

In one model of the cognitive processes that support attempts at thought suppression, Wegner (1992, 1994; Wegner, Ansfield, & Pilloff, 1998) has suggested that regulation of one's conscious thoughts may rely on the action of two distinct mental processes that operate over different temporal periods and subserve different aspects of thought suppression. One process is believed to maintain an active representation of to-be-avoided cognitions in mind and is therefore hypothesized to be tonically engaged during attempts to suppress an unwanted thought. In contrast, the second process is thought to direct the reengagement of additional control processes necessary for a return to successful thought suppression following the occurrence of an unwanted thought; thus, this process is hypothesized to be transiently engaged following failures of thought suppression.

Interestingly, this description of the processes underlying successful mastery over one's thoughts directly parallels more recent neural models of cognitive control (Braver, Barch, Gray, Molfese, & Snyder, 2001; Braver, Reynolds, & Donaldson, 2003; Cohen, Botvinick, & Carter, 2000; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000; Miller & Cohen, 2001), which have suggested a dissociation between the control processes subserved by the prefrontal cortex (PFC) and those subserved by the anterior cingulate cortex (ACC). In contrast to earlier suggestions that these regions make similar and undifferentiated contributions to executive processing (Duncan & Owen, 2000), these recent accounts suggest that the PFC specifically subserves control mechanisms that support active

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maintenance of the requirements of a novel or underlearned task, whereas the ACC contributes to executive function by monitoring for conflict signals that indicate the need for additional control (e.g., mutually exclusive response tendencies). As suggested by Miller and Cohen (2001) in their review of prefrontal function, "demands for control are associated with an increase in PFC activity; . . . the ACC responds selectively to conflict in processing" (p. 191). That is, whereas the PFC can be thought of as implementing "preemptive" control that strategically deploys attention in anticipation of future conflicts, the ACC gives rise to "consequential" control that responds contingently to on-line conflicts in processing (Matsumoto & Tanaka, 2004).

Recently developed techniques for the analysis of functional magnetic resonance imaging (fMRI) data now permit a test of the hypothesized differences in the temporal scope of PFC- and ACC-mediated control processes. These techniques have allowed researchers to isolate the neural signatures associated with sustained changes in cognitive processing from those associated with more transient, moment-to-moment processes (Burgund, Lugar, Miezin, & Petersen, 2003; Donaldson, Petersen, Ollinger, & Buckner, 2001; Velanova et al., 2003; Visscher et al., 2003). For example, Donaldson et al. (2001) have used these techniques to distinguish sustained aspects of memory performance—the state of being in a particular retrieval mode—from more transient aspects of recognition, such as successfully retrieving a particular item from memory.

In the current study, we adapted these analytic techniques to examine differences in the time course of PFC and ACC contributions to cognitive control during attempts at thought suppression. By employing a task in which subjects were asked to prevent specific thoughts from entering consciousness, we capitalized on the natural parallel that has emerged between cognitive models of thought suppression (Wegner, 1992, 1994; Wegner et al., 1998) and neural models of executive control (Cohen et al., 2000; Kerns et al., 2004; MacDonald et al., 2000; Miller & Cohen, 2001). Just as the former have suggested that suppression engages both sustained and transient control processes, the latter have suggested dissociations in the neuroanatomical basis of these different aspects of control. Specifically, we examined both (a) the sustained difference in neural activation between prolonged attempts to suppress an unwanted thought and periods of free thought and (b) transient differences in activation between the occurrence of a specific thought during attempts at suppression (when the thought was forbidden) and its occurrence during free thought (when it was permissible). Combining insights from cognitive and neural models of control, we expected to observe greater sustained PFC engagement throughout attempts at thought suppression, compared with free-thought periods, and greater transient ACC activation in response to the occurrence of a forbidden thought, compared with a permissible thought.

METHOD

Subjects and Task

The subjects were 17 (9 male; mean age = 22.8, range = 19–28) right-handed, native English speakers with no history of neurological problems. Informed consent was obtained in a manner approved by the Committee for the Protection of Human Subjects at Dartmouth College.

Subjects were scanned while alternately trying to suppress thoughts about a specific target (a white bear) or thinking freely about any topic whatsoever, including the target item. In each of six functional runs, subjects performed blocks of three different tasks, each of which was cued by the color of a traffic light presented on screen throughout the run. During suppress blocks (cued by a red traffic light), subjects attempted to avoid thinking about a white bear for 120 s. During free-thought blocks (cued by a green traffic light), subjects were free to think about anything at all (including a white bear) for 120 s. In both conditions, subjects made a button response whenever they thought about a white bear, thereby enabling us to distinguish neural activity associated with thoughts that differed only in respect to whether they were forbidden (occurring during the suppress task) or permissible (occurring during the free-thought task). Note that because subjects were asked to make a button press for occurrences of the target thought during both the suppress and the free-thought blocks, they had the same active task in both conditions.

Suppress and free-thought blocks were separated by 28-s blocks of a manual-response task. During these blocks, a yellow traffic light flashed at pseudorandom intervals, and subjects were asked to press a response button whenever the light went on or off. The yellow light remained on screen for an interval between 1,500 and 2,500 ms, was absent for 1,500 to 2,500 ms, then appeared again, and so on. The order of blocks within each functional run was as follows: (a) manual-response block; (b) suppress or free-thought block, randomly selected; (c) manual-response block; and (d) suppress or free-thought block, whichever had not yet occurred.

Functional Imaging and Analysis

The fMRI data were collected in six functional runs (each lasting 296 s) on a 1.5-T GE Signa scanner (GE, Milwaukee, WI) using a gradient spin-echo echo-planar pulse sequence sensitive to blood-oxygenation-level-dependent (BOLD) contrast (repetition time = 2 s, echo time = 35 ms, flip angle = 90°, 3.75 × 3.75 in-plane resolution). Each functional run consisted of 148 axial scans (20 slices, 5 mm thick, 1-mm skip). The fMRI data were analyzed using the general linear model (GLM) in SPM99 (Wellcome Department of Cognitive Neurology, London, United Kingdom). Preprocessing of functional data consisted of slice timing correction, motion realignment, normalization to the Montreal Neurological Institute (MNI) stereotaxic space, and spatial smoothing (8-mm full-width/half-maximum Gaussian kernel).

Following analytic procedures for distinguishing sustained from transient changes in the fMRI BOLD signal (Burgund et al., 2003; Donaldson et al., 2001; Velanova et al., 2003; Visscher et al., 2003), we coded sustained effects associated with the suppress and free-thought conditions into the GLM as a regressor with a boxcar shape, equal in width to the duration of one task block (120 s). Button presses during suppress and free-thought blocks were used to model two event types: forbidden and permissible thoughts about a white bear, respectively. Transient effects associated with forbidden and permissible thoughts were coded in the GLM by delta function regressors for each of the 10 frames (20 s) following a button press, thus spanning the time it takes for the hemodynamic response to decay to baseline (Boynton, Engel, Glover, & Heeger, 1996; Miezin, Maccotta, Ollinger, Petersen, & Buckner, 2000). In addition, a regressor for the baseline signal and a regressor for the linear drift in the MR signal were coded in the GLM. Comparisons of interest were implemented as linear contrasts. Individual contrast images were then submitted to a second-level, random-effects analysis to create mean *t* images. Regions of interest were defined using a statistical criterion of 5 or more contiguous voxels exceeding an uncorrected voxel-wise threshold of $p < .001$. Although these criteria resulted in an experiment-wide alpha level that was more lenient than $p < .05$, the strong a priori nature of the predictions weighed against the added possibility of Type I errors.

RESULTS

Behavioral Data

Earlier cognitive research has demonstrated that, paradoxically, explicit attempts to suppress a thought often serve to increase the occurrence of that very thought (Wegner, 1992, 1994; Wegner et al., 1998). The behavioral results of the present experiment were consistent with these demonstrations that attempts to suppress a thought are often unsuccessful: Across all six functional runs, subjects reported roughly equal numbers of forbidden (M = 42.6, SD = 32.2) and permissible (M = 39.4, SD = 22.8) thoughts about the white bear, $t(16) < 1$, n.s.

fMRI Data

We first identified regions that demonstrated greater sustained activation during suppress than free-thought blocks. Three distinct functional regions were identified from this analysis: right dorsolateral PFC (middle frontal gyrus; see Fig. 1), right ventrolateral PFC (inferior frontal gyrus), and a left posterior region that extended from the caudate nucleus to the ventral-most extent of the supramarginal gyrus (see Table 1). Analysis of the parameter estimates obtained from each of these regions demonstrated significantly greater sustained activation during suppress than during free-thought blocks, but no evidence of transient differences between forbidden and permissible thoughts (all *t*s < 1.31, all *p*s > .21, all p_{rep} values < .708). No regions demonstrated significantly greater sustained activation during free-thought than suppress blocks.

Next, we identified regions that demonstrated greater transient activation during forbidden thoughts (occurring during suppress blocks) than during permissible thoughts (occurring during free-thought blocks). A number of regions demonstrated such transient differences (see Table 2); these regions included bilateral ACC (Fig. 2). In each of the regions identified in this comparison, greater transient activation was observed for forbidden than for permissible thoughts, but a sustained difference was observed only at a single locus in occipital cortex (MNI coordinates = 21, −84, 0). In all the other regions, no sustained difference was obtained between suppress and free-thought blocks (all *t*s < 1.34, all *p*s > .20, all p_{rep} values < .716). Moreover, no regions demonstrated significantly greater transient activation during permissible than during forbidden thoughts.

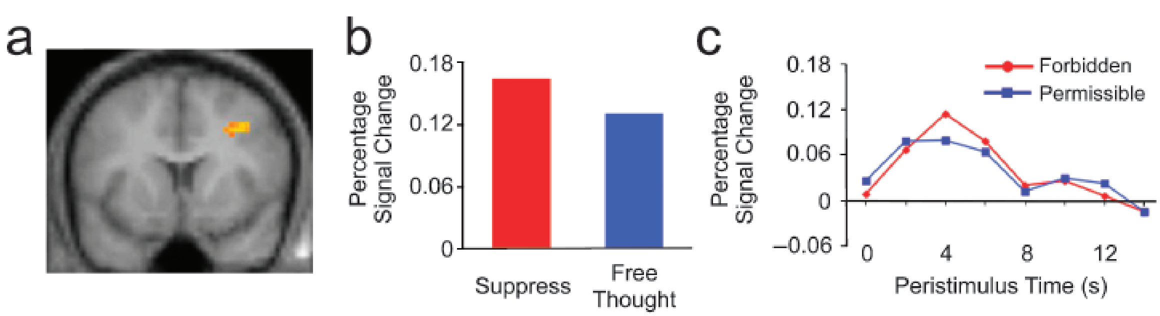

Fig. 1. Sustained activation in dorsolateral prefrontal cortex (PFC) during periods of thought suppression. This region, shown on a coronal slice of subjects' mean normalized brain (a), demonstrated greater sustained activation during thought-suppression blocks than during free-thought blocks, but no transient differences between forbidden and permissible thoughts. The graphs display (b) the mean percentage signal change associated with the sustained effects of the thought-suppression and free-thought tasks in this dorsolateral PFC region and (c) the event-related hemodynamic response associated with the transient response to forbidden and permissible thoughts.

TABLE 1

Regions Showing Greater Sustained Activation in Suppress Than in Free-Thought Blocks

Region	Coordinates x	y	z	Maximum t	p	p_{rep}
Dorsolateral PFC	33	12	36	3.90	< .002	.988
	24	15	36	3.48	< .004	.979
Inferior frontal gyrus	48	21	12	3.29	< .005	.973
Caudate nucleus to SMG	−24	−33	24	4.47	< .001	.995
	−30	−45	30	3.64	< .003	.983
	−21	−45	21	3.22	< .006	.970

Note. The t tests reflect the statistical difference between the two conditions, as computed by SPM99; p_{rep} provides an estimate of the probability that a replication with the same power will support the original finding. Coordinates refer to the Montreal Neurological Institute stereotaxic space. PFC = prefrontal cortex; SMG = supramarginal gyrus.

DISCUSSION

Our results are consistent with predictions derived from both cognitive and neural models: Attempts at suppressing an unwanted thought produced both sustained and transient increases in control that were associated with concomitant increases in activation in dorsolateral PFC and ACC, respectively. Specifically, a right-lateralized region of dorsolateral PFC was identified by contrasts that were sensitive to differences in sustained activation during extended attempts at thought suppression (relative to blocks of free thought). In contrast, activation in bilateral ACC increased in conjunction with transient occurrences of the forbidden thought (compared with occurrences of the same thought when it was permissible).

TABLE 2

Regions Showing Greater Transient Activation During Forbidden Than During Permissible Thoughts

Region	Coordinates x	y	z	Maximum t	p	p_{rep}
Anterior cingulate cortex	−12	48	12	4.10	< .001	.991
	15	45	6	4.53	< .001	.995
Internal capsule, head of caudate	−15	0	12	4.20	< .001	.992
	18	−12	18	4.35	< .001	.994
Posterior cingulate	−12	−15	39	5.42	< .001	.999
	−6	−21	33	4.43	< .001	.994
Central sulcus	−36	−18	54	4.91	< .001	.997
Supramarginal gyrus	−60	−33	27	4.58	< .001	.995
Superior parietal gyrus	30	−42	57	3.82	< .002	.987
Collateral sulcus	−21	−45	−9	4.58	< .001	.995
	18	−51	−12	4.90	< .001	.997
Occipital horn of lateral ventricle	27	−54	6	4.23	< .001	.993
Lateral occipital sulcus	51	−63	0	7.28	< .001	> .999
Occipital cortex	30	−72	24	4.65	< .001	.996
	−6	−81	−3	6.56	< .001	> .999
	−42	−81	0	5.48	< .001	.999
	21	−84	0	8.02	< .001	> .999

Note. The t tests reflect the statistical difference between the two conditions, as computed by SPM99; p_{rep} provides an estimate of the probability that a replication with the same power will support the original finding. Coordinates refer to the Montreal Neurological Institute stereotaxic space.

These results are consistent with two aspects of current models of cognitive control (Cohen et al., 2000; MacDonald et al., 2000; also see Braver et al., 2001, 2003). First, they confirm that both PFC- and ACC-mediated processes are engaged by conditions that require increased levels of cognitive control. Second, and more critically, these data also provide converging evidence that the temporal scopes of PFC contributions to cognitive control and ACC contributions to cognitive control differ substantially, a central prediction of extant models of cognitive control. These models contrast with views that the PFC and ACC contribute equipotentially to "difficult" cognitive tasks (Duncan & Owen, 2000) by instead suggesting that whereas PFC-mediated control is sustained throughout tasks that require executive processing, ACC-mediated control is transiently engaged during specific episodes that require additional control.

It is important to note that transient increases in ACC-mediated control were observed in this study despite the absence of response competition. Much of the experimental (van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) and simulation-based (Botvinick, Braver, Barch, Carter, & Cohen, 2001) evidence supporting the conflict-monitoring view of ACC function has involved processing conflicts at the level of response output, that is, when competing behavioral responses become active. As Botvinick et al. (2001) noted in their review of ACC function, relatively little evidence has yet emerged to suggest that the ACC resolves nonresponse conflicts. The current results speak to this issue by providing some of the first evidence of ACC engagement during purely cognitive competition (see also Johnson et al., 2005); the only overt conflict experienced by subjects was the incompatibility between their goal state ("I should not think about a white bear") and the actual state of the system ("Oops, I'm thinking about a white bear"). Although a motor response was required upon suppression failures, no simultaneously competing behavioral response was engaged. Thus, the ACC may contribute to the resolution of conflict at a purely cognitive level, in the absence of any behavioral or perceptual competition.

At the same time, the lack of continual behavioral responses in the current paradigm leaves open the possibility that subjects may not have accurately reported all occurrences of the target thought. Therefore, the results may underestimate the true frequency of forbidden thoughts (presumably, subjects rarely indicated that they had made an error when in fact they had not). However, we note that any systematic underreporting of target thoughts would merely have attenuated our ability to detect differences between forbidden and permissible thoughts, thereby increasing the possibility of Type II error, but could not

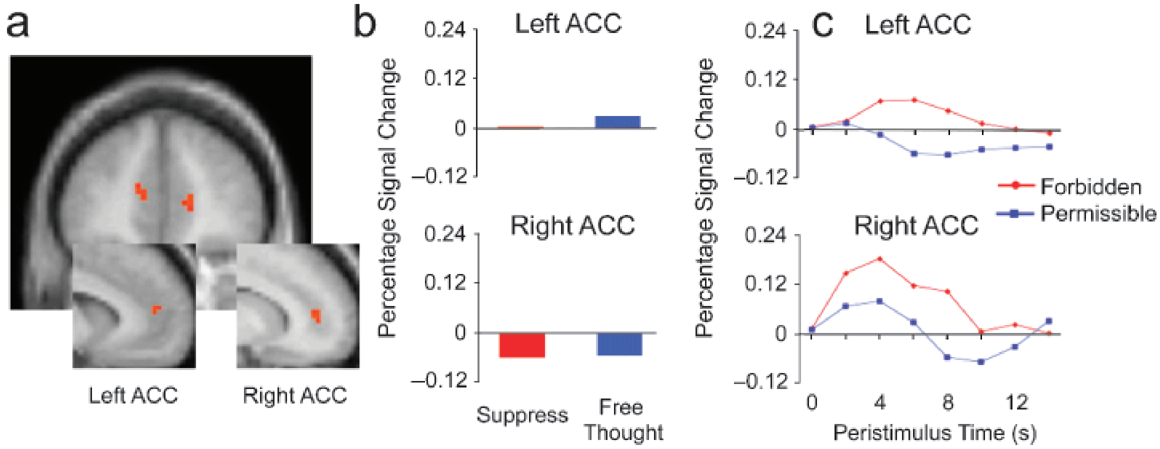

Fig. 2. Transient activation in bilateral regions of the anterior cingulate cortex (ACC) during forbidden thoughts. These regions, shown on a coronal slice (a), demonstrated greater transient activation associated with forbidden thoughts than with permissible thoughts, but no sustained differences between the thought-suppression and free-thought blocks. The inset in (a) shows the same left and right ACC regions overlaid on the anterior portion of a sagittal slice. The graphs display (b) the mean percentage signal change associated with the sustained effects of the thought-suppression and free-thought tasks in both left and right ACC and (c) the event-related hemodynamic response associated with the transient response to forbidden and permissible thoughts.

account for the significant transient differences actually observed between trial types.

By combining neural and cognitive models, the current experiment can contribute simultaneously to understanding of the functional neuroanatomy of cognitive control and to psychological theories of how humans successfully regulate the contents of consciousness. First, we have provided support for the hypothesis that the PFC and ACC contribute to cognitive control over different time scales. Second, we suggest that the ACC may participate in the resolution of purely cognitive conflicts that do not include competition between incompatible behavioral responses or perceptual inputs. Finally, our findings speak directly to a long-standing cognitive theory of how individuals accomplish the regulation of their own thoughts (Wegner, 1992, 1994; Wegner et al., 1998), adding functional neuroanatomical support to earlier notions that successful thought suppression relies on both sustained and transient aspects of cognitive control. We believe this kind of interplay between cognitive and neural theory will continue to open fruitful avenues of inquiry for psychologists and cognitive neuroscientists alike.

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