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Attention Control, Memory Updating, and Emotion Regulation Temporarily Reduce the Capacity for Executive Control

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This research tested the hypothesis that initial efforts at executive control temporarily undermine subsequent efforts at executive control. Four experiments revealed that controlling the focus of visual attention (Experiment 1), inhibiting predominant writing tendencies (Experiment 2), taking a working memory test (Experiment 3), or exaggerating emotional expressions (Experiment 4) undermined performance on subsequent tests of working memory span, reverse digit span, and response inhibition, respectively. The results supported a limited resource model of executive control and cast doubt on competing accounts based on mood, motivation, or task difficulty. Prior efforts at executive control are a significant contextual determinant of the operation of executive processes.

Keywords: emotion regulation, executive control, limited resources, self-regulation, working memory

People have a remarkable ability to alter their behavioral tendencies. For instance, over 40 million Americans are former cigarette smokers, including some who conquered pack-a-day habits virtually overnight (Centers for Disease Control, 2005). Most people harbor prejudices that favor their own groups and devalue other groups, but people often refrain from acting on those prejudices (e.g., Devine, 1989). Even reflexive behaviors can be overridden. A loud flash of noise typically causes the eyes to blink with pronounced force, yet people may reduce or inhibit the startle eyeblink response (Jackson, Malmstadt, Larson, & Davidson, 2000).

These examples all reflect a capacity for the executive control of behavior. Although theorists disagree about its precise definition, *executive control* is generally considered a collection of interrelated abilities that enables people to modify their thoughts and actions (Baddeley, 1986; Norman & Shallice, 1986). Simply said, people may purposefully pursue some thoughts or behaviors and inhibit others, thereby expanding the range and variability of human achievement. The purpose of the present investigation was to test the hypothesis that executive control operates like a limited resource. More precisely, the current research tested the extent to which initial efforts at executive control undermined subsequent efforts at executive control, as though the initial efforts depleted a resource needed to perform well at the subsequent attempts.

Executive control is among the most compelling capacities of the human mind, and researchers from nearly every subdiscipline of psychology study it. Neuroscientists scan healthy brains, test lesioned brains, and dissect dead brains to locate the physical systems that underlie executive control (e.g., Rajkowska, 1997; Rypma, Berger, & D'Esposito, 2002). Clinical psychologists examine how people manage their emotions and overcome their addictions to better understand executive dysfunction (e.g., Brandon et al., 2003; Gross & Munoz, 1995). Social psychologists explore the willful delay of gratification and the inhibition of prejudice to discover the dynamics of executive control (e.g., Macrae, Bodenhausen, & Milne, 1998; Mischel, Shoda, & Rodriguez, 1989). And cognitive psychologists ask people to remember, to forget, and to juggle several tasks at once to identify the processes involved in executive control (e.g., Anderson, 2003; Baddeley, 1996; Kane & Engle, 2000; Norman & Bobrow, 1975).

One prominent and fruitful approach has been to examine individual differences in the capacity for executive control. The evidence shows that people with superior capacities to focus attention while ignoring distractions outperform people with inferior capacities on several measures of cognitive ability, including reading comprehension (Daneman & Carpenter, 1980), decision making (Hinson, Jameson, & Whitney, 2003), and logical reasoning (Kane et al., 2004). Such evidence verifies the influence of executive control across a wide swath of mental life. One consequence of this focus on individual differences, however, has been a relative lack of attention toward situational or contextual determinants of executive capacity. Not only does executive capacity differ between individuals, but also it fluctuates within individuals over time.

An important exception to the individual differences approach has been research examining the influence of concurrent tasks or cognitive loads on executive control. This research has shown that executive control is undermined by concurrent activity, particularly concurrent activity that is effortful or attention demanding. For example, people are less able to inhibit a response when they

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must actively maintain other information in working memory at the same time (e.g., Lavie, Hirst, de Fockert, & Viding, 2004; Ward & Mann, 2000). Hence individual differences in executive capacity and the nature of the person's concurrent activity both help to determine whether any given attempt at executive control will succeed.

Whereas the effects of concurrent activity on executive control are increasingly well understood, the effects of prior activity are relatively unknown. Research showing that concurrent activity undermines executive control has implicitly assumed that, when the cognitive load has been lifted, executive control reverts immediately to baseline capacity. The present research tested the alternate prediction that efforts at executive control temporarily deplete a limited resource, and in the interim before the resource is replenished, further attempts at executive control are prone to failure. Evidence to support this prediction would indicate that recent efforts at executive control are a potent situational determinant of executive capacity.

Limited Resources, Self-Regulation, and Executive Control

The hypothesis that the capacity for executive control becomes depleted with use is based on evidence that the self-regulation of behavior consumes an internal resource, akin to energy or strength. More precisely, Baumeister, Bratslavsky, Muraven, and Tice (1998) found that performing one act of self-regulation undermined performance on subsequent, unrelated acts of self-regulation. For instance, forcing oneself to eat radishes instead of chocolates reduced persistence at a subsequent task, and suppressing emotional distress impaired subsequent performance at solving anagrams. In both cases, initial efforts at self-regulation appeared to deplete the same resource needed to perform well at subsequent efforts. Resource depletion has now been linked to several behavioral problems, including overeating (Vohs & Heatherton, 2000), intellectual underachievement (Schmeichel, Vohs, & Baumeister, 2003), and impulsive aggression (DeWall, Baumeister, Stillman, & Gailliot, 2007). All of those problems appear to be hastened by prior efforts at self-regulation.

Self-regulation has been defined as any attempt to override or alter one's thoughts, feelings, or behaviors (Barkley, 1997; Baumeister, Schmeichel, & Vohs, in press; Metcalfe & Mischel, 1999). As such, self-regulation shares a high degree of conceptual overlap with executive control, yet research and theory regarding the two constructs has remained separate, and only occasional efforts have been made to connect them. The present work sought to connect a limited resource view of self-regulation to the operation of putative executive control functions.

It seems fair to say that, relative to research on self-regulation, research on executive control has focused more intently on identifying the specific processes that enable the flexible modification of thought and behavior. For example, Shimamura's (2000) dynamic filtering model posits four executive control processes underlying the self-regulation of behavior: *selecting,* or focusing attention on particular subsets of the mental or physical environment; *maintaining,* or keeping goals or other information active in working memory over time; *updating,* or manipulating the contents of working memory; and *rerouting,* or switching from one task or mental set to another. Similarly, factor analytic work by Miyake and colleagues (Miyake et al., 2000) revealed three moderately distinct executive control functions, namely inhibiting prepotent responses, updating working memory, and set shifting or rerouting.

Relative to research on self-regulation, research on executive control also has been more explicitly informed by neuroscientific evidence regarding brain structure and function. For example, the dynamic filtering model explicitly links executive processes such as selecting and updating the contents of working memory to activity in the frontal lobes (Shimamura, 2000). Indeed, executive control processes are increasingly identified with activation of the anterior cingulate cortex, the orbitofrontal cortex, and the dorsolateral prefrontal cortex, respectively (e.g., Braver & Cohen, 2000; Miller & D'Esposito, 2005; Smith & Jonides, 1999).

On the other hand, research on self-regulation has tended to adopt a more contextual approach, focusing on the situational determinants of behavioral self-regulation more so than the brain systems or specific processes underlying such regulation. Consider, for example, research showing that resisting tempting chocolates undermined later task persistence (Baumeister et al., 1998). Task persistence probably required several executive control processes, such as focusing attention, inhibiting the impulse to give up, and updating working memory to meet the requirements of the task. Which of those processes were affected by prior efforts to resist the tempting chocolates? Similarly, which executive processes were involved in resisting temptation that may have undermined subsequent persistence?

The current investigation sought to hone in on the particular processes that deplete executive capacity by having participants perform putative executive control tasks and then tracking the aftereffects on unrelated attempts at executive control. Research has shown that response inhibition depletes an internal resource required for further self-regulation (Richeson & Trawalter, 2005; for a review, see Vohs & Schmeichel, in press), so it was reasonable to assume that inhibition would undermine subsequent efforts at executive control. However, whether other processes such as memory maintenance and memory updating have similar aftereffects has yet to be established. Although some theorists consider both maintenance and updating to be executive processes, updating is clearly the more demanding of the two processes. To update information in memory requires information to be maintained in an active state and also transformed in some way, whereas maintenance requires no transformative cognitive operations (Smith & Jonides, 1999). Hence it was plausible that memory updating would be particularly likely to deplete executive capacity, insofar as updating requires more executive control than maintenance does. Any differential aftereffects stemming from the two processes may help to distinguish what does deplete executive capacity from what does not.

The current work also sought to identify those forms of executive control that are impaired by prior efforts at executive control. Previous evidence indicated that response inhibition is impaired by prior attempts at executive control (Muraven, Tice, & Baumeister, 1998). However, the extent to which memory maintenance and memory updating are impaired by prior executive control has yet to be established. Any dissociation in the consequences of prior executive control for later inhibition, updating, and maintenance may shed light on the boundaries of the hypothesized resource depletion effect.

In sum, the present research tested the extent to which a contextual factor—the prior exertion of executive control—reduces executive resources and therefore undermines the subsequent operation of executive control. This was accomplished by administering several combinations of consecutive executive tasks to determine precisely which forms of executive control were implicated in the process.

Overview of Present Research

This investigation sought converging evidence for the executive resource hypothesis using a multimethod approach because there is no single, gold-standard measure of executive control, nor is there a single, unambiguous manipulation to deplete executive capacity. Hence each experiment featured a different manipulation to deplete capacity, including attention control (Experiment 1), response inhibition (Experiment 2), memory updating (Experiment 3), and response exaggeration (Experiment 4). Likewise, the experiments included four different target measures of executive control ability, including three measures of memory updating (operation span, sentence span, and reverse digit span) and a measure of response inhibition. This approach was crucial to establishing support for the view that executive control generally, and not some specific process, impairs and is in turn impaired by contiguous efforts at executive control. The diverse methods also helped to reveal the generality of the depletion effect and reduced the possibility of drawing conclusions based on methodological artifact. Thus the convergence across experiments was intended to be more informative than any single experiment could be.

Each experiment also sought to probe the mechanisms and address alternate explanations for the predicted effects. In Experiments 1, 2, and 4, mood states were measured after the initial manipulation of executive control to determine whether mood and arousal helped to explain the predicted aftereffects. When appropriate, working speed also was assessed so that the influence of prior executive control on this aspect of performance could be evaluated. And Experiment 3 tested the idea that performing any difficult or effortful task, even if it did not require executive control, was sufficient to deplete capacity and undermine later efforts at executive control.

Experiment 1: Effects of Attention Control on Subsequent Working Memory Span

The first experiment tested the hypothesis that performing one executive control task undermines performance on a subsequent executive control task, as if performing the first task depleted a resource required for further efforts at executive control. In the first phase of the experiment, participants watched a short television presentation under instructions to ignore distracting information at the bottom of the screen or under instructions simply to watch the presentation. Thus, one group exercised executive control by focusing attention and ignoring on-screen distractions, whereas the other group attended freely to any and all parts of the screen (borrowed from Gilbert, Krull, & Pelham, 1988).

After the television presentation and a mood measure, participants performed a test that tapped the ability to update working memory while performing a concurrent distractor task. Several such tests of working memory span have been developed, with some tests combining a recall task with concurrent mathematical calculations (e.g., operation span task; Turner & Engle, 1989) and others combining recall with verbal or spatial distractors (e.g., sentence span task; see Conway et al., 2005). To establish the robustness of the hypothesized depletion effect, I had some participants perform the operation span task and some perform the sentence span task.

The prediction in both cases was that careful attention control during the television presentation would reduce later working memory span, because the attention control task would have depleted the capacity to update working memory. Impaired working memory would be evident in poorer recall of target words, poorer performance on the distractor tasks, or both. Some evidence suggests that the distractor tasks (simple mathematical calculations and rote recognition memory) are achieved by automatic or routine cognitive processes that do not require a great deal of executive control (e.g., Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Muraven et al., 1998). If that is correct, then performance on the distractor tasks may proceed unaffected by prior efforts at executive control even as recall performance is impaired.

Method

Participants. One hundred forty-five undergraduate students (109 women, 36 men) participated in exchange for credit toward a course requirement. Only students who had not performed the same memory test in a different study were included in the sample. Data from 4 participants were excluded from all analyses because these participants reported trying to memorize the distracting words during the initial viewing task (described below). Thus, the final sample was 141 students.

Materials and procedure. In the first phase of the experiment, participants watched a 6-min video clip depicting a woman being interviewed by an off-camera interviewer. The clip was played without audio, purportedly because the experiment concerned impressions of others' nonverbal behavior. In addition to the woman being interviewed, a series of common one-syllable words (e.g., *play*) appeared on the screen for 15 s each. The words were printed in black, framed by a white background, and confined to the bottom third of the screen. Thus, the words were clearly visible but did not dominate the main action on the screen (i.e., the interview). None of the words appeared on the subsequent memory test.

Approximately half the participants were randomly assigned simply to watch the woman being interviewed and were given no instructions regarding the words at the bottom of the screen (no control condition). The other participants were instructed to watch the interview and also to "avoid looking at or reading any words that may appear on the screen" (attention control condition). Because attention automatically orients toward novel stimuli in the environment (Shiffrin & Schneider, 1977), these participants had to exercise executive control to ignore the words and focus only on the woman in the scene. After viewing the clip, all participants completed the Brief Mood Inspection Survey (BMIS; Mayer & Gaschke, 1988) as a measure of mood and arousal, and then the experimenter explained the working memory task.

Working memory measures. In the second (final) phase of the experiment, participants performed either the operation span task or the sentence span task. Participants who performed the operation span task evaluated math equations and also encoded and recalled target words. For example, participants saw *(9 × 3) – 1 = 2* and had to indicate ("Yes" or "No") whether the given answer was correct. (In the example, the correct answer was "No.") Then participants read a target word (e.g., *house*) for later recall. One target word was presented after each equation. Thus, participants read an equation, evaluated whether it was correct, read a target word, and then advanced to the next equation, the next target word, and so on. Participants saw two, three, four, or five equation–word pairings before being prompted to recall the target words in the set, and they did not know in advance how many words a set would include. Participants worked through 15 sets totaling 48 equation–word pairings in all, presented in the same order for each participant.

The operation span task was administered on a computer, and participants controlled the presentation of stimuli with their responses. Test duration and accuracy on the "Yes/No" evaluations of the math equations were recorded. Participants were guided through two practice trials before formal task performance began.

Participants who performed the sentence span task heard a sentence, answered a multiple-choice question about the sentence, and later tried to recall the final word from each sentence in a set. For example, the experimenter read aloud a sentence such as "The passengers on the train were happy." Then participants consulted a question sheet that contained one multiple-choice question for every sentence read by the experimenter. In this example, the relevant question was "Where were the passengers?", and the response options were "On the plane," "On the boat," and "On the train." (The correct answer was "On the train.") After participants selected a response, they heard the next sentence, responded to a short question about it, and so on. Participants performed sets of two, three, four, or five of these sentence–question combinations before being prompted to recall the final word from each sentence in the set, and they did not know in advance how many sentences a set would include. Participants completed 2 practice sets and then 15 experimental sets, totaling 50 sentences in all. The sentences were presented in the same order for each participant, and the experimenter surreptitiously recorded the duration of the memory test for each participant.

After performing their respective working memory tests, participants rated the difficulty of watching the interview clip as instructed. This measure served as a check of the effort required to accomplish the initial viewing (attention control) task.[1] Participants also rated the difficulty of the memory task. Both ratings were made on a scale from 1 (*not at all difficult*) to 7 (*very difficult*). Last, participants were debriefed, thanked, and dismissed.

Results

Manipulation check. Ratings of the difficulty of the initial viewing task verified that the attention control instructions ($M = 4.77$, $SD = 1.64$) were more difficult to follow than the no control instructions ($M = 2.78$, $SD = 1.63$), $F(1, 137) = 50.46$, $p < .001$. This pattern is consistent with the view that the attention control task required effortful executive control.

Working memory performance. The primary goal of Experiment 1 was to determine whether attention control reduces the capacity for executive control, as measured by subsequent tests of operation span and sentence span, respectively. Both tests afforded five measures of performance (one measure of performance on the distractor task and four measures of recall: total words, number of word sets, number of words in full sets, and the single longest set; see Conway et al., 2005). Each performance measure was standardized within test type (because the two tests differed in length and content), and the resulting z scores were analyzed with 2 (attention control vs. no control) × 2 (test type: operation span vs. sentence span) analyses of variance (ANOVAs). Table 1 displays the raw performance scores. The test type variable had no main or interactive effects on any of the performance measures (Fs < 1), so all subsequent analyses collapsed across test type and focused on the main effect of the attention control manipulation on subsequent working memory performance.

Each of the recall measures offered strong support for the executive depletion hypothesis. Participants who had previously exercised attention control scored worse than participants who had not previously attempted attention control. Specifically, participants in the attention control condition scored worse in terms of recall of individual words on the test, $F(1, 137) = 7.01$, $p = .009$, $d = 0.42$; sets of words recalled correctly, $F(1, 137) = 9.37$, $p = .003$, $d = 0.53$; total words in correctly recalled sets, $F(1, 137) = 9.01$, $p = .003$, $d = 0.51$; and the single longest set recalled correctly, $F(1, 137) = 7.44$, $p = .007$, $d = 0.45$. Altogether, the recall patterns confirmed that the operation of working memory was impaired by prior efforts at attention control.

Regarding performance on the distractor tasks, the attention control manipulation did not reliably influence the number of incorrect responses to the math problems (attention control $M = 1.95$ vs. no control $M = 1.54$), $F(1, 77) = 1.30$, $p = .26$, $d = 0.26$, or the number of incorrect responses to the sentence comprehension questions (attention control $M = 0.32$ vs. no control $M = 0.35$), $F < 1$, $d = 0.05$. Thus, the attention control manipulation impaired recall, but performance on the distractor tasks was unaffected. This may reflect a floor effect, insofar as all participants had a low rate of incorrect responses on the distractor tasks, or perhaps the distractor tasks were accomplished with automatic and routine processes that did not depend on executive resources.

Further, because the duration of the working memory tests was determined by the speed with which participants gave responses, it was possible that the attention control manipulation affected later working speed, and this may have influenced the observed performance patterns. For example, participants who initially exercised attention control may have exhibited poorer recall because they lacked the motivation to perform well and so rushed through the subsequent test. This was not the case. The attention control ($M =$

[1] Executive control involves active attempts to modify thoughts or behaviors. This should be perceived and rated as more difficult than the relative absence of executive control. Although some nonexecutive tasks may be rated as difficult or effortful (e.g., Muraven et al., 1998), task difficulty is often considered a proxy for efforts at self-regulation or executive control (Naccache et al., 2005; Vohs & Schmeichel, 2003).

Table 1
Working Memory Span by Test Type and Condition (Experiment 1)

	Working memory measure							
	Sets recalled		Longest set		Words in correct sets		Total recall	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Operation span test								
No control ($n = 38$)	7.65	2.52	3.41	0.93	18.92	8.69	34.68	5.50
Attention control ($n = 41$)	6.33	2.28	3.10	0.76	15.00	6.56	32.88	4.15
Sentence span test								
No control ($n = 31$)	8.52	2.82	4.03	0.75	23.03	10.14	38.32	6.42
Attention control ($n = 31$)	7.16	2.71	3.55	0.96	18.23	8.84	34.87	6.62

398.42 s, $SD = 62.20$ s) and no control ($M = 394.96$ s, $SD = 69.04$ s) groups took equivalent amounts of time to complete the tests ($F < 1$, $d = 0.05$). (Test duration was similar across the two test types, $F < 1$, and there was no hint of a Viewing Condition × Test Type interaction, $F < 1$.) Insofar as time on task reflects motivation or effort, these findings suggest the attention control manipulation did not affect the effort expended on the memory tests. Thus, the observed differences in working memory capacity were likely not due to changes in working speed or motivation, nor to differences in test-taking strategy as indicated by performance on the distractor tasks.

Self-reported mood and test difficulty. The next set of analyses tested whether the attention control manipulation affected participants' moods. If carefully controlling attention while viewing the interview resulted in more negative affect or more arousal than simply viewing the interview, then performance in the second phase of the experiment may have been affected by these subjective states. The mood measure (the BMIS) was administered after the viewing task and furnished separate scores for mood valence and arousal. Participants in the attention control condition reported somewhat less positive mood ($M = 8.49$, $SD = 11.05$) than did participants in the no control condition ($M = 12.19$, $SD = 10.90$), $F(1, 137) = 3.72$, $p = .06$, $d = 0.34$. The effect of viewing condition on arousal was slight and nonsignificant ($F < 1$, $d = 0.16$).

Because the attention control manipulation had a marginal effect on mood valence, the analyses of recall performance reported above were repeated in an analysis of covariance that included mood valence as a covariate. The pattern of results was unchanged: Prior efforts at attention control still led to poorer recall on the working memory tests (ps $< .01$).

At the end of the experiment, participants rated the difficulty of the memory test they had taken. Participants in the attention control condition ($M = 5.18$, $SD = 1.25$) rated the test as somewhat more difficult to perform than did participants in the no control condition ($M = 4.75$, $SD = 1.49$), $F(1, 137) = 3.51$, $p = .06$. There are at least two explanations for this marginal difference in subjective difficulty. One explanation is that attention control participants were somewhat aware of their substandard performance, and they attributed their performance to the difficulty of the test. The other is that initial efforts to control attention exhausted the capacity to update working memory, so the test actually was more difficult in this depleted state than when executive capacity was intact. Although the latter interpretation is consistent with the executive resource hypothesis, the present experiment cannot distinguish between these two possibilities.

Discussion

Experiment 1 supported the hypothesis that exerting executive control temporarily reduces the capacity for executive control. Participants who focused attention toward only part of a television screen while ignoring on-screen distractions performed worse on a subsequent test of working memory span than did participants who attended to any and all parts of the screen. The decline in performance that followed the attention control task was consistent across two different tests of working memory span. Prior efforts at attention control undermined recall on both the operation span task (which included numerical distractors) and the sentence span task (which included verbal distractors), and mood states, motivation, and working speed did not appear to account for the impairment. Hence it appeared that controlling attention impaired subsequent efforts to update the contents of working memory, as if the initial act depleted a resource required for both attempts at executive control.

Experiment 2: Effects of Response Inhibition on (Reverse) Digit Span

Experiment 2 sought to replicate and extend the results from Experiment 1 to different independent and dependent variables. The guiding hypothesis was that efforts at executive control temporarily deplete executive capacity, but Experiment 2 used a response inhibition task rather than an attention control task to manipulate initial efforts at executive control and tests of digit span rather than working memory span to measure subsequent executive capacity.

Response inhibition is widely considered to require executive control (Barkley, 1997; Miyake et al., 2000; von Hippel & Gonsalkorale, 2005). In Experiment 2, some participants wrote a story under instructions not to use two common letters, namely *a* or *n,* so that participants in this condition would constantly have to inhibit the use of the forbidden letters and find alternative ways to express their thoughts. The other participants wrote a story with no restrictions on which letters they could use. Only the group that wrote without using the letters *a* and *n* was expected to show evidence of reduced executive capacity.[2]

Next, participants encoded several series of digits and attempted to recall them. On some trials, participants attempted to recall digits in the order in which they had been presented (forward span), and on other trials, they attempted to recall digits in reverse order (reverse span). Both forward span and reverse span were measured to probe the specificity of the aftereffects of the response inhibition task. Competing predictions could be made. Some models, such as Shimamura's (2000) dynamic filtering model, consider both memory maintenance and memory updating to be executive control processes. If that is accurate, then both forward span and reverse span should be reduced by prior efforts at executive control. Other approaches, however, consider updating to be an executive control process but do not consider maintenance to be so, particularly when maintenance does not also involve ignoring or inhibiting competing information (e.g., D'Esposito, Postle, Ballard, & Lease, 1999; Smith & Jonides, 1999). Hence the conservative prediction was that reverse span would be reduced by prior efforts at response inhibition, but forward span would not be reduced, though it was plausible that forward span would be somewhat affected.

Method

Participants. Sixty-one undergraduate students (31 women, 30 men) participated in exchange for credit toward a course requirement.

Procedure. In the first phase of the experiment, participants wrote a short story describing a trip they had taken recently. Participants randomly assigned to the controlled writing condition were instructed not to use the letters *a* or *n* anywhere in their story. Thus, these participants exercised executive control by inhibiting the use of two frequently used letters. Letter usage in the free writing condition was unrestricted so that participants in this condition did not have to inhibit any particular writing tendency. The experimenter stopped all participants after 6 min of writing and gave them a mood measure, the BMIS (Mayer & Gaschke, 1988), before administering the memory test.

The procedure for the memory test during the second (final) phase of the experiment was as follows. Single digits were presented on a viewing screen for 3 s each. After a set of three, five, seven, or nine digits had been presented, participants were prompted to recall the digits in the set. After half of the sets, participants were instructed to recall the digits in the order in which they were presented (forward span). For the other half, participants attempted to recall the digits in reverse order (reverse span). Participants had 15 s to recall a set, then the next set was presented, and the presentation–recall cycle was repeated. There were 32 sets in all (8 of each set size), and the order of their presentation was randomly determined. Participants did not know in advance whether a set was to be recalled in forward or reverse order.

After finishing the memory test, participants completed a follow-up questionnaire by rating the difficulty of the initial writing task and also the difficulty of the memory test (on scales from 1 = *not at all* to 7 = *very*). Finally, participants were debriefed regarding the purpose of the experiment, thanked for their participation, and dismissed.

Results

Manipulation check. Participants in the controlled writing condition rated the writing task more difficult ($M = 6.45$, $SD = 1.33$) than did participants in the free writing condition ($M = 1.49$, $SD = 1.18$), $F(1, 59) = 239.37$, $p < .01$, $d = 3.95$. This pattern is consistent with the view that inhibiting the use of common letters while writing required effortful executive control.

Digit span performance. The primary hypothesis was that prior efforts at response inhibition would reduce reverse digit span but have little or no effect on forward digit span. This hypothesis was confirmed. A 2 (controlled writing vs. free writing) × 2 (forward span vs. reverse span) mixed-factorial ANOVA on total recall revealed a significant within-subjects effect of memory span type, $F(1, 59) = 19.60$, $p < .01$, partial $\eta^2 = .25$, such that participants recalled more digits in the forward span trials than in the reverse span trials, and a significant between-subjects effect of writing condition, $F(1, 59) = 5.23$, $p < .05$, partial $\eta^2 = .08$. Relative to participants in the free writing condition, participants in the controlled writing condition performed worse overall. Most important, the interaction between writing condition and memory type was significant, $F(1, 59) = 6.29$, $p < .05$, partial $\eta^2 = .10$, such that the effect of writing condition emerged only in the case of reverse span. Table 2 displays the means. Participants who inhibited the use of *a* and *n* on the writing task showed poorer recall on the subsequent memory test, but only when recall required memory updating (i.e., reverse span).

Next, repeated measures ANOVAs examined the effect of writing condition on recall across the four set sizes. First, regarding forward span, the main effect of set size was significant, $F(3, 177) = 157.90$, $p < .001$, partial $\eta^2 = .73$, such that shorter sets were recalled correctly more often than longer sets. Both the writing condition ($F < 1$, partial $\eta^2 = .01$) and Condition × Set Size terms ($F < 2$, $p = .13$, partial $\eta^2 = .03$) fell short of statistical significance. These patterns suggest once again that prior executive control did not reliably alter memory maintenance.

Regarding reverse span, the within-subjects effect of set size was significant, $F(3, 177) = 155.91$, partial $\eta^2 = .73$, such that shorter sets were recalled correctly more often than longer sets. Here, as expected, the writing condition main effect was significant, $F(1, 59) = 10.49$, $p < .01$, partial $\eta^2 = .15$. The Condition × Set Size term did not reach statistical significance, $F(3, 177) = 1.53$, $p = .21$, partial $\eta^2 = .03$. Tukey's post hoc tests revealed that controlled writing (compared with free writing) impaired reverse span for three-digit sets ($p < .01$, $d = 0.97$), five-digit sets ($p < .06$, $d = 0.49$), and seven-digit sets ($p < .05$, $d = 0.53$). No differences on correct recall of nine-digit sets emerged ($p = .75$, $d = 0.06$), likely because both groups recalled on less than one of these sets on average. These patterns indicate that prior efforts at response inhibition impaired memory updating.

[2] In another condition, participants wrote a story without using the letters *q* or *z*. Given the infrequent use of these letters, having to inhibit any tendency to use them should not deplete executive capacity. Indeed, this group did not differ from the free writing condition on either forward or backward digit span performance or any of the subsidiary measures. Comparing the controlled writing (no *a* or *n*) condition to this (no *q* or *z*) group revealed the same pattern of results as comparing the controlled writing condition to the free writing condition.

Table 2
Forward Digit Span and Reverse Digit Span by Condition (Experiment 2)

Condition	3 digits		5 digits		7 digits		9 digits		Total	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Forward span										
Free writing ($n = 29$)	3.85	0.44	3.49	0.49	2.18	1.31	0.67	0.78	9.18	2.08
Controlled writing ($n = 32$)	3.82	0.55	3.57	0.63	1.68	0.90	0.71	0.85	8.79	1.75
Reverse span										
Free writing ($n = 29$)	3.88	0.33	3.33	0.82	2.18	1.18	0.33	0.48	8.72	1.92
Controlled writing ($n = 32$)	3.39	0.63	2.89	0.96	1.57	1.10	0.29	0.66	7.14	1.88

Note. Means represent the number of sets recalled correctly.

Self-reported mood. After the writing task but before the memory test, participants reported their mood and arousal level. I examined whether the initial writing manipulation produced group-wide differences in these subjective states, but no differences emerged (Fs < 2, ps $> .15$, ds < 0.40). Including mood valence and arousal as covariates in the analyses of memory performance did not alter the results reported above. Thus, as in Experiment 1, mood or arousal did not appear to account for the derogatory aftereffects of executive control.

Subjective evaluations of the tasks. At the end of the experiment, participants rated the difficulty of the memory test. Participants in the two conditions did not differ in terms of how difficult they found the test ($F < 1$, $d < 0.05$). Thus, the marginal between-groups difference in test difficulty observed in Experiment 1 was not replicated in Experiment 2. Participants also evaluated how well they had done on the memory test, which could indicate whether prior efforts at response inhibition influenced perceptions of memory performance in addition to actual performance. Participants rated their performance slightly lower in the controlled writing condition ($M = 3.86$, $SD = 1.30$) than in the free writing condition ($M = 4.33$, $SD = 1.27$), although this difference was not statistically significant, $F(1, 59) = 2.09$, $p = .15$, $d = 0.37$. Hence there was little evidence to suggest that the writing manipulation altered subjective assessments of the memory test, but there was ample evidence that it altered objective performance.

Discussion

Experiment 2 supported the hypothesis that reduced executive capacity, caused by prior efforts at executive control, undermines further attempts to exercise executive control. Relative to participants who wrote freely, participants who inhibited the use of common letters while writing were subsequently less effective at recalling strings of digits in reverse order. Forward digit span was not affected to the same extent. Hence the effect of prior executive control was specific to later performance that required both maintaining and updating the contents of memory, whereas maintenance alone was spared.

The findings suggest that both inhibiting responses and updating information in memory relied on a shared underlying capacity, whereas maintaining information in memory did not rely on the same capacity. Probably most theorists do not consider maintenance to require executive control (D'Esposito et al., 1999; Kane et al., 2004; but see Shimamura, 2000). Maintaining information in memory often requires attention and effort, and maintenance is crucial for the performance of innumerable tasks. However, maintenance does not require inhibition or other executive operations to transform or update information. Maintenance excites less activation in the dorsolateral prefrontal cortex than updating does, which is another hint that maintenance requires relatively less executive control (Smith & Jonides, 1999). Presumably, the requirement to transform the digits in memory rendered the reverse span measure sensitive to reduced executive capacity. Performance on the forward span measure, because it did not require this transformative cognitive operation, was relatively unaffected.

Experiment 3: Effects of Updating Versus Maintenance on Later Emotional Regulation

Experiment 3 attempted a more liberal and dramatic test of the idea that executive control is a depletable capacity by measuring the aftereffects of cognitive control on efforts at emotion control. The prevailing hypothesis was that initial efforts at executive control undermine subsequent efforts. However, several investigators have suggested that cognitive control and emotion control occur in different areas of the frontal lobes. For example, the dynamic filtering model posits that the executive control of memory and the executive control of emotion emanate from different areas of the prefrontal cortex (Shimamura, 2000; see also Compton et al., 2003; Stone, Baron-Cohen, & Knight, 1998). Consistent with this view are one study's findings that lesions to an area associated with cognitive control (dorsolateral prefrontal cortex) did not disrupt emotion control, whereas lesions to the orbitofrontal cortex did disrupt emotion control (Rule, Shimamura, & Knight, 2002). Hence it was plausible that initial efforts to control memory would have little or no effect on subsequent efforts to control emotional responding because these may rely on different areas of the brain.

In Experiment 3, participants performed either a memory maintenance task or a memory updating task and then attempted to inhibit responses to an emotionally charged stimulus. The prediction was that, relative to participants who performed the maintenance task, those who performed the updating task would be less successful at inhibiting their emotional responses, as though updating memory temporarily depleted the capacity for executive control of emotion.

Within this basic framework, Experiment 3 also sought to address an alternate account of the predicted results, namely that performing any effortful or difficult task reduces the capacity for executive control. According to this account, expending effort undermines subsequent executive processes regardless of whether the effort was devoted to executive control. Experiment 3 investigated this possibility by comparing the aftereffects of three different tasks that varied in difficulty. In one condition, participants performed the operation span task, which required executive control in the form of updating working memory. In the other two conditions, participants performed tasks that required short-term memory maintenance. The two maintenance tasks differed in terms of difficulty, but neither of them required executive control.[3] If effort expenditure or the difficulty of a task is responsible for subsequent decrements in executive control, then performance on the emotion inhibition task should reveal a linear pattern such that inhibition is poorest after the updating task and best after the easy maintenance task, with inhibition after the moderately difficult maintenance task falling somewhere in between. If, however, only efforts at executive control reduce executive capacity, then inhibition ability should be poorest after the updating task but equally good after the two maintenance tasks.

To make the comparison between the aftereffects of effort expenditure versus executive control even more rigorous, the maintenance tasks were made to last approximately 6 min longer than the updating task. If performing the updating task impairs response inhibition relative to performing the more time-consuming maintenance tasks, then the conclusion that exerting executive control, rather than effort, is responsible for depleted executive capacity would be considerably strengthened.

Method

Participants. Forty-five undergraduate students (14 women, 31 men) participated in exchange for credit toward a course requirement. Data from one additional participant were excluded from analyses because this participant answered a phone call during the response inhibition task.

Materials and procedure. Participants performed one of three randomly assigned memory tests at the start of the experiment. In the working memory condition, participants performed the operation span task. Participants in this condition completed a slightly longer version of the task (16 sets totaling 56 equation–word pairings in all) than the one used as the dependent variable in Experiment 1. In the other two conditions, participants evaluated the same mathematical equations and encoded and recalled the same target words, but these tasks were not intermixed. Rather, they were performed separately. In the short-term memory–2 (STM-2) condition, participants encoded two target words and then attempted to recall them immediately thereafter, and this procedure was repeated 28 times. In the short-term memory–6 (STM-6) condition, participants encoded 6 target words and then attempted to recall them, and this procedure was repeated 9 times; and on a 10th trial, they encoded and recalled 2 words, for a total of 56 target words in all. Either immediately before or immediately after completing their respective short-term memory tests, participants evaluated 56 mathematical equations. Thus, all participants evaluated the same equations and attempted to remember the same target words, but only for participants in the working memory condition were these tasks intermixed, and hence only in the working memory condition was executive control required.

After their respective memory tests, all participants watched an emotionally charged film clip under instructions to "keep your face perfectly expressionless as you watch; that is, try to inhibit your outward emotional response to the film clip." The film clip lasted 2 min and depicted gruesome scenes from an animal slaughterhouse. This clip has been shown to elicit a high degree of negative affect (Schmeichel, Demaree, Robinson, & Pu, 2006). Participants' faces were videotaped as they watched the film clip so that their emotional expressivity could be rated.

After the film clip, participants rated the extent to which they felt depressed, tense, sorry, dissatisfied, and anxious on scales from 1 (*not at all*) to 5 (*extremely*). Responses to these items were summed to form an index of negative affect ($\alpha = .74$), which was used to examine whether subjective response to the film clip differed across condition. Participants also rated the difficulty of their initial memory task on a scale from 1 (*not at all difficult*) to 7 (*extremely difficult*). At the end of the experiment, participants were debriefed, thanked, and dismissed.

Results

Manipulation checks. As intended, the STM-2 task was less difficult than the STM-6 task, which in turn was less difficult than the operation span task. Participants correctly recalled a higher proportion of word sets in the STM-2 condition ($M = 0.99$) than in the STM-6 condition ($M = 0.53$), with participants in the working memory condition recalling the lowest proportion of sets ($M = 0.37$); all comparisons, $p < .05$. The ratings of task difficulty revealed the same pattern. The STM-2 task was rated as less difficult ($M = 1.88$, $SD = 1.02$) than the STM-6 task ($M = 2.93$, $SD = 1.27$), which was rated as less difficult than the operation span task ($M = 4.67$, $SD = 1.05$); all comparisons, $p < .05$. Thus, the three tasks differed in terms of difficulty.

Further, both the STM-2 task ($M = 864.06$ s, $SD = 65.57$ s) and the STM-6 task ($M = 850.54$ s, $SD = 28.74$ s) took more time to complete than did the operation span task ($M = 565.07$ s, $SD = 113.63$ s), $ps < .05$. The two STM tasks did not differ in duration.

Inhibition of emotional responding. After their respective memory tasks, participants attempted to inhibit their responses to an emotionally charged film clip. Participants were videotaped as they watched the gruesome scenes, and three judges, working independently, later viewed the tapes and rated how emotionally expressive participants' faces were on a continuous scale from 1 (*not at all*) to 111 (*extremely*). The ratings of the coders were highly interrelated ($\alpha = .90$), so they were averaged to form a single measure of emotional expressivity.

A one-way ANOVA on the emotional expressivity score revealed significant variation among the groups, $F(2, 42) = 3.26$,

[3] Maintaining information in memory has been linked to activity in the prefrontal cortex, and so some models consider maintenance to be an executive control process. Other models consider updating or actively manipulating the contents of memory to require executive control but exclude simple memory maintenance. The results of Experiment 2, in which updating but not maintenance was impaired by prior efforts at executive control, were consistent with the latter view. The predictions in Experiment 3 were based on the assumption that updating depletes executive capacity but maintenance does not, and this assumption was explicitly tested by comparing the aftereffects of maintenance versus updating.

$p < .05$. The means are displayed in Table 3. Planned contrasts indicated that, relative to participants who had taken either the STM-2 test or STM-6 test, participants who had taken the working memory test expressed more emotion on their faces, indicating poorer response inhibition (ps $< .05$, ds $> .65$). Emotional expressivity in the STM-2 and STM-6 conditions did not differ from each other. Using the natural log of the expressivity score (to reduce skew) as the dependent variable revealed the same pattern of significant results. Hence the inhibition of emotional responding was impaired after performing the operation span task relative to performing an easy or a moderately difficult short-term memory task.

Self-reported mood. Negative affect was measured immediately after the film clip to determine whether the initial memory tests differentially influenced participants' subjective response to the film clip. The negative affect measure revealed no differences among the groups ($F < 1$). The means on the negative affect index were as follows: working memory, $M = 8.13$ ($SD = 2.97$); STM-2, $M = 8.56$ ($SD = 2.92$); and STM-6, $M = 9.07$ ($SD = 1.40$). Altogether, the results indicated that participants had similar subjective responses to the film clip regardless of which memory test they had taken, but those who had taken the working memory test were less successful at inhibiting the outward expression of that internal emotional response.

Discussion

Experiment 3 again supported the hypothesis that efforts at executive control temporarily deplete a resource needed for later, unrelated attempts at executive control. Participants who had performed a memory updating task were less successful at inhibiting their emotional expressions relative to participants who had performed a memory maintenance task. This finding is notable in light of previous research indicating that the executive control of memory and the executive control of emotion emanate from different areas of the brain (Rule et al., 2002; Stone et al., 1998). Hence it was plausible that updating memory and inhibiting emotional responses would draw on different processing resources, in which case the performance of one of those tasks may not influence the subsequent performance of the other. The data revealed the opposite result, however: Performing cognitive control undermined later efforts at emotion control. Apparently the aftereffects of executive control are not strictly limited to performances that activate identical areas of the frontal lobes.

The results of Experiment 3 also argued against the idea that task difficulty determines the magnitude of subsequent decrements in executive capacity. Participants performed one of three tasks that differed in terms of difficulty, but only one of the tasks (the operation span task) required executive control. If the difficulty of a task determines its aftereffects, then the results should have shown a linear pattern in subsequent inhibition performance, such that inhibition was most impaired after the hardest task and least impaired after the easiest task, with inhibition after the moderately difficult task falling somewhere in between. Contrary to this, the results revealed that inhibition was equally successful after the easy and moderately difficult nonexecutive tasks but was substantially impaired after the executive control task. Hence it appeared that the executive requirements of the initial task were the decisive determinant of subsequent inhibition ability.

Table 3
Inhibition of Emotional Responding by Condition (Experiment 3)

Condition	Expressed emotion M	Expressed emotion SD
STM-2 ($n = 15$)	9.18	8.21
STM-6 ($n = 15$)	9.57	10.36
Working memory ($n = 15$)	25.64	32.56

Note. Higher means indicate poorer inhibition. STM = short-term memory.

Experiment 4: Effects of Response Exaggeration on Later Working Memory Span

In each of the previous experiments, the initial executive control task always involved some form of cognitive control, including attention control (Experiment 1), response inhibition (Experiment 2) and memory updating (Experiment 3). These diverse cognitive control tasks had similar aftereffects, but the exclusive use of cognitive control as the initial task limits the generalizability of the results. Specifically, it remains to be seen whether attempts to control emotional responses deplete the capacity for executive control in the same way attempts to control attention and memory do. Hence a fourth and final experiment sought converging evidence by assessing the aftereffects of controlling emotional responses.

Moreover, Experiment 4 extended the previous studies to test whether exaggerating responses rather than inhibiting them undermines later executive control. Most accounts of executive control highlight the importance of both activating or prioritizing particular responses and inhibiting or suppressing other responses. Exaggerating emotional responses seems closely aligned with the former executive control function. More than simply maintaining a response, exaggeration requires the person actively to increase or enhance the intensity of a response. Insofar as this requires executive control, subsequent efforts at executive control should suffer.

Participants in Experiment 4 viewed two short film clips that were intended to elicit negative emotions. Some participants were instructed to exaggerate the outward expression of their emotions as they watched, whereas other participants were instructed simply to express their emotions. The dependent measure of executive capacity was performance on a working memory test. The prediction was that exaggerating emotional responses would deplete the capacity for executive control and so disrupt subsequent efforts to update working memory.

Comparing the aftereffects of exaggerating versus expressing negative emotional responses also helped to address the role of emotion in the hypothesized effects. In Experiments 1 and 2, participants who had recently attempted executive control reported feeling about as good as participants who had not attempted executive control, so differences in emotional states did not account for subsequent differences in the operation of executive control processes. Experiment 4 took a different approach by inducing negative emotions in all participants prior to the target executive control test. If negative emotion has a powerful influence on executive control, then the results may show that the manner in which participants viewed the distressing film clip was irrelevant to the subsequent operation of executive control, as long as the viewing instructions did not alter participants' emotional state. In contrast, if prior executive control is the more potent determinant of executive capacity, then exaggerating versus expressing responses may undermine executive control regardless of participants' emotional state.

Method

Participants. Sixty-five undergraduate students (52 women, 13 men) participated in exchange for credit toward a course requirement. Only students who had not taken the operation span test in a different study earlier in the term were included in the sample.

Procedure. In the first phase of the experiment, participants watched two 2-min film clips. One clip depicted a disgusting eye surgery (see Gross & Levenson, 1995), and the other clip depicted sad children describing family hardships (e.g., a young boy describes the death of his infant brother). Approximately one half of the participants were randomly assigned to watch the film clips and were given no instructions regarding response regulation (express condition). The other participants were instructed to watch the clips and to exaggerate their emotional response (exaggerate condition). Specifically, these participants were instructed to "try to express what you are feeling very clearly on your face; that is, exaggerate your outward emotional response as you watch the film clip." After viewing the film clips, participants completed a state measure of mood and arousal, the BMIS (Mayer & Gaschke, 1988).

The procedure for the operation span task during the second (final) phase of the experiment was identical to the procedure used in Experiment 1. Once again, recall performance, math performance, and test duration were recorded. After finishing the operation span task, participants rated the difficulty of watching the film clips as instructed (on a scale from 1 = *not at all* to 7 = *very*), then were probed for suspicion, debriefed about the purpose of the experiment, and thanked for their participation.

Results

Manipulation checks. Participants rated the exaggerate instructions as somewhat more difficult to follow ($M = 3.88$, $SD = 2.04$) than the express instructions ($M = 3.00$, $SD = 1.94$), $t(63) = 1.77$, $p = .08$. This pattern lends support to the idea that the viewing instructions varied the exertion of effortful executive control.

To verify that participants in the exaggeration condition expressed more emotion than participants in the express condition, two judges, working independently, watched the videotapes of participants' faces and rated them in terms of expressed emotion and expressed arousal (on scales from 0 = *none* to 90 = *a lot*). The ratings of the coders were highly interrelated ($\alpha = .91$), so they were averaged to form a single measure of emotional expressivity. As intended, exaggerators displayed more emotion ($M = 67.84$, $SD = 20.15$) than expressers did ($M = 54.42$, $SD = 24.74$), $t(63) = 2.39$, $p < .05$. Thus, participants in the exaggeration condition reliably increased their outward emotional display.

Working memory measure. The primary hypothesis was that response exaggeration, relative to response expression, reduces subsequent working memory span. The operation span task afforded four measures of recall (longest set, number of sets in full, number of words in full sets, and total words recalled). (As in Experiment 1, errors on the math portion of the test were infrequent in both groups, $F < 1$, $d = .10$.) Three of the four recall measures supported the executive depletion hypothesis. Table 4 displays the means. Compared with those in the express condition, participants in the exaggerate condition scored worse in terms of the total number of sets recalled correctly, $t(63) = 3.18$, $p = .002$, $d = 0.79$; the span of the single longest set recalled correctly, $t(63) = 2.03$, $p = .046$, $d = 0.51$; and the total number of words in the correctly recalled sets, $t(63) = 3.16$, $p = .002$, $d = 0.78$. Total number of words recalled correctly across the entire test (i.e., from both full and partial sets) revealed that both groups recalled a similar number of words overall ($t < 1$, $d = 0.04$). Altogether, the patterns indicated that working memory span was reduced by prior efforts at executive control, with three of four span measures revealing a significant detriment due to prior response exaggeration.

Because the duration of the memory test varied with the speed with which participants gave responses, it was possible that groupwide differences in the time to complete the task influenced the recall patterns. This was not the case. Exaggerators ($M = 571.88$ s, $SD = 87.96$ s) and expressers ($M = 554.21$ s, $SD = 94.45$ s) took an equivalent amount of time to complete the working memory task ($t < 1$). Insofar as time spent on task reflects effort expenditure, this finding suggests the two groups did not differ in terms of effort expended on the task.

Self-reported mood. The next set of analyses examined whether exaggerating versus expressing responses to the distressing scenes differentially affected participants' emotional states. If exaggerating responses produced a different emotional state than simply expressing responses, then executive control in the second phase of the experiment may have been affected by group-wide differences in emotional state. The BMIS was administered immediately after the film clips and furnished separate scores for mood valence and arousal. Exaggerators and expressers reported similar subjective states: For valence, exaggerate $M = 5.13$ ($SD = 10.89$), and express $M = 8.45$ ($SD = 11.01$); for arousal, exaggerate $M = 26.16$ ($SD = 5.82$), and express $M = 24.97$ ($SD = 6.98$), both ts < 1, ds < 0.31. As in the previous experiments, including mood and arousal as covariates in the analyses of recall did not alter the patterns described above. Thus, differential mood states did not appear to account for the observed effects.

Table 4
Operation Span by Condition (Experiment 4)

	Working memory measure							
	Sets recalled		Longest set		Words in correct sets		Total recall	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Express response ($n = 33$)	6.79	2.43	3.58	0.61	18.24	7.95	39.33	5.68
Exaggerate response ($n = 32$)	4.88	2.42	3.22	0.79	12.31	7.15	38.91	5.56

Discussion

Experiment 4 found that exaggerating the expression of negative emotional responses reduced subsequent working memory span. These results conceptually replicated the findings in the previous experiments and extended them to show that the executive control of emotional responding undermines later efforts at updating memory. Thus, although the executive control of memory and the executive control of emotion may emanate from distinct areas of the brain (Rule et al., 2002), performing one of these temporarily impaired the performance of the other.

The results of Experiment 4 argued against the emotion and arousal alternatives to the resource depletion hypothesis. The manipulation of executive control in Experiment 4 involved exaggerating versus merely expressing responses to distressing film clips. Exaggerators appeared more distressed and more aroused than expressers, but both groups reported similar emotional experiences, consistent with evidence that modifying negative emotional expressions does not alter subjective mood states (Gross & Levenson, 1993; Schmeichel et al., 2006). Thus, memory updating was impaired by prior attempts to control emotional responses above and beyond any effect of negative emotion that stemmed from watching the distressing scenes.

General Discussion

The purpose of this investigation was to examine the aftereffects of exercising executive control. The four experiments support four major conclusions. First, the results reveal that initial efforts at executive control undermine later efforts at executive control. Second, the results indicate that different forms of executive control have remarkably similar aftereffects. Ignoring distractions while attending to one portion of a television screen (Experiment 1) and exaggerating facial expressions of emotion (Experiment 4) both reduced later working memory span, and inhibiting a predominant writing tendency (Experiment 2) impaired later attempts to update working memory. Similarly, updating working memory reduced the ability to inhibit emotional responding (Experiment 3). Hence the observed deficits stemmed from diverse efforts at executive control rather than one specific process such as inhibition.

Third, the results reveal that the aftereffects of executive control are specific to executive control processes and do not disrupt attention and memory more generally. For example, Experiment 2 found that attempts to maintain and update information in memory (reverse span) were impaired by prior efforts at executive control, whereas attempts simply to maintain information in memory (forward span) were relatively unaffected. This pattern reveals a boundary separating the processes that were impaired by prior efforts at executive control from the processes that were not affected. After exerting executive control, participants were perfectly able to marshal attention and effort to encode information and retrieve it from memory, but they were less effective at marshaling executive processes to update or transform the information.

Last, the findings support the view that executive control operates like a limited and depletable resource. The state of the resource (sufficient or depleted) exerted a potent influence on the operation of executive control. This conclusion is consistent with previous evidence that self-regulatory capacity fluctuates over time, as though self-regulation relies on a limited resource (see Muraven & Baumeister, 2000). Insofar as executive processes such as attention control, response inhibition, and memory updating ultimately enable the self-regulation of behavior (Beer, Shimamura, & Knight, 2004; Feldman Barrett, Tugade, & Engle, 2004), the present results suggest that previous demonstrations of depleted self-regulatory resources may more precisely be considered instances of reduced resources for executive control.

Limited Resources and Executive Control

In an influential article that sought to characterize the role of cognitive resources in the performance of simultaneous tasks, Hirst and Kalmar (1987) identified three metaphors for cognitive resources: fuel, structure, and skill. Though the present work examined the performance of consecutive tasks, not simultaneous ones, it is nonetheless instructive to evaluate the present findings in light of the three metaphors described by Hirst and Kalmar.

The first metaphor posits a reservoir of fuel that powers particular cognitive processes, so that the operation of those processes depends on available levels of the essential fuel. The hypothesis that executive processes are powered by a limited resource or fuel motivated the current investigation, and the findings fit the fuel metaphor quite well. The results of all four experiments support the idea that initial efforts at executive control temporarily deplete the reservoir of fuel needed to perform well at subsequent executive control tasks.

The idea that executive control processes depend on a limited resource or fuel may be more than a metaphor. Previous research found that an infusion of glucose into the bloodstream boosted memory performance, particularly when encoding occurred under conditions of divided attention (Sünram-Lea, Foster, Durlach, & Perez, 2002). Hence one of the brain's major sources of energy (i.e., glucose; Laughlin, 2004; Siesjo, 1978) may correlate with the efficacy of executive control (Benton, Owens, & Parker, 1994). Most relevant to the current experiments is evidence that glucose levels statistically mediated the effects of one self-regulation attempt on subsequent self-regulation attempts (Gailliot et al., in press). Whether putative executive control processes such as response inhibition and memory updating also fluctuate in step with blood glucose has yet to be established, and further efforts to identify the biochemical underpinnings of executive control represent a promising avenue for future research.

According to the structure metaphor, particular processes may be impaired when two or more tasks place demands on the same elements of the cognitive architecture at the same time. The structure metaphor sheds light on the inability to perform some tasks simultaneously (such as listening to two voices at once), but it does not seem to provide an adequate explanation for performance on consecutive tasks. For instance, Experiment 3 found that initial efforts to update working memory undermined subsequent efforts to suppress emotional responses, though these two forms of executive control likely placed demands on different areas of the brain (e.g., Richards & Gross, 2000; Rule et al., 2002). Hence it was not the case that initial efforts at executive control impaired only later performances that relied on the same components of the cognitive architecture. Initial efforts at executive control impaired even subsequent performances that were likely to recruit activity in different regions of the frontal lobes.

I hasten to note that the current research did not measure brain activity directly. Future work using functional MRI and other brain-localization techniques may find that the structure metaphor does help to explain performance on consecutive executive control tasks. For example, activity in the prefrontal cortex may be particularly difficult or costly to sustain (e.g., Benton et al., 1994; Marois & Ivanoff, 2005), and this may contribute to the pattern of poorer executive control after prior efforts. Or perhaps consecutive efforts at executive control place demands on the same brain structures that disrupt the operation of those structures.

The third resource metaphor, the skill metaphor, implies that the resource for executive control processes is not limited in the sense of being fixed or finite. Rather, executive control may be improved with practice, learning, or changes in strategy. The skill metaphor seems wholly inconsistent with the idea that practice causes temporary deficits in skill, yet this is closest to the observed patterns of results. Hence the skill metaphor does not adequately capture the present findings.

It may be that longer time intervals between efforts at executive control are required for the benefits of practice to emerge. Put another way, efforts at executive control may deplete fuel in the short-term but build skill over the long-term. Research on self-regulation has found some evidence to support this idea. A few weeks of regular practice at self-regulation made resources more resistant to temporary depletion (Muraven, Baumeister, & Tice, 1999; Oaten & Cheng, 2006), much like regular walking or jogging renders the heart muscle more resistant to fatigue. The idea that practice builds executive resources over time merits additional research.

The picture that emerges depicts the fuel, structure, and skill metaphors as compelling and complementary views of executive control, though the fuel metaphor received the strongest support in the present investigation. Future work that measures brain activity from one executive control process to the next will permit a more decisive test of the structure metaphor, whereas evidence for long-term benefits of practicing executive control may lend support to the skill view. Theories of executive control stand to benefit from programmatic research that seeks to integrate insights from all three metaphors. This may involve examining both the short-term and long-term consequences of exercising executive control for brain activity, blood glucose levels, and the efficacy of executive control processes. The present results represent an initial step in such a research program, but future work incorporating longitudinal methods and biological and chemical measures is needed.

Limitations and Alternative Explanations

Several theorists have criticized the usefulness and the explanatory power of resource models like the one tested here (e.g., Meyer & Kieras, 1997; Navon, 1984). One common criticism of resource models concerns their lack of specificity. What activities consume the resource, and precisely how does the resource operate? The current experiments found evidence that the resource at issue was relevant only for specific kinds of activity. Only tasks that required response modulation or memory updating impaired, and were impaired by, contiguous efforts at executive control. Other, simpler activities such as encoding and recalling information were not implicated to the same extent. Hence the resource was essential specifically for putative executive control processes rather than cognitive processes generally.

The current findings also cast doubt on several alternatives to the limited resource view. Specifically, the aftereffects of executive control were not attributable to changes in emotional state or reductions in motivation. Nor did cognitive overload explain the findings. One possibility was that initial efforts at executive control would linger in awareness or occupy memory even after they had been completed, and this would help to explain the decrements on later, unrelated tasks. Several sources of evidence contradict this possibility. For example, in Experiment 2, inhibiting responses did not undermine later memory maintenance, whereas cognitive load does undermine memory maintenance (e.g., Szmalec, Vandierendonck, & Kemps, 2005). Thus, prior efforts at executive control had a different effect on maintenance than cognitive load typically does. Note also that in each experiment, participants performed one task and then prepared to perform a second, unrelated task. A period of 1 to 5 min separated the two tasks, providing ample time for any lingering activation from the initial task to dissipate. Altogether, then, the results did not conform to a cognitive load account. Nevertheless, research that measures the lingering activation of prior executive control efforts or, better yet, research that compares directly the effects of concurrent versus prior activity is needed to draw firm conclusions regarding the relative merits of the two competing explanations.

Another interpretation of the aftereffects of executive control is that they reflect a response to performing any difficult or effortful task. By this account, whether prior efforts required executive control is unimportant; what matters is the difficulty of those efforts. Experiment 3 found evidence to contradict this possibility insofar as performing a working memory task undermined later executive control relative to performing one of two short-term memory tasks. It is crucial that the two short-term memory tasks differed in terms of difficulty, but no differences in subsequent executive control emerged after performance of these tasks. Moreover, whereas the working memory task took 10 min to complete, the short-term memory tasks took approximately 15 min to complete. The shorter task that required executive processes, then, had a more damaging aftereffect than the longer tasks that did not require executive processes, which is consistent with the idea that efforts at executive control rather than concerted efforts at any task deplete the capacity for executive control.

Implications

The present findings have several implications for the theories of executive control. For one, these experiments suggest that the capacity for executive control is not constant. Hence individual differences in executive capacity tell only part of the story, because prior efforts at executive control also influence the efficacy of executive processes. The extent to which prior efforts at executive control and individual differences in baseline capacity interact to influence executive processes remains to be seen. Future research may uncover individual differences in other relevant dimensions as well, such as the rate at which exertion consumes executive resources or the rate at which executive control recovers from depletion.

The present results also pertain to the issue of whether executive control is a unitary capacity or whether it is composed of distinct subcapacities or abilities. In the current work, attention control, response inhibition, and response exaggeration all had highly similar and detrimental effects on later attempts at executive control. These results lend support to the view that executive control is a unitary capacity insofar as different executive tasks influenced each other across time, and surface distinctions among the tasks did not conceal their connection. The current results fit with factor analytic evidence that several tests of cognitive control share a common underlying factor (e.g., Kane et al., 2004). Future factor analytic studies may profit by including more disparate tests of executive control ability, for example, tests of emotion control as well as tests of cognitive control, because these may share a reliance on a common underlying capacity. This suggestion is not meant to minimize the importance of distinguishing among different forms of executive control. Indeed, a thorough treatment of executive control demands close attention to the various forms executive control may assume. The current findings examined several forms of executive control and found compelling evidence for their interconnectivity and relatedness.

Further, the resource depletion approach may help to identify which putative executive control processes rely on a shared underlying capacity and which do not. This may help to establish the boundaries of the executive control construct. Experiment 2, for example, revealed that performing a response inhibition task impaired later attempts to update memory but did not impair attempts to maintain information in memory, suggesting that inhibition and updating, but not maintenance, shared a common basis. Future research may investigate whether other processes such as task switching and short-term spatial memory also rely on what appears to be a limited resource for executive control.

The current findings also have implications for behavior. Updating memory and controlling attention are important in their own right, but they also contribute to attempts to restrict eating, spending, and drinking, to name just a few relevant behaviors. Activities that deplete the capacity for executive control may influence success at such behaviors. For example, recent evidence revealed that people were more likely to violate self-imposed drinking limits on days that included relatively more efforts at self-regulation (Muraven, Collins, Morsheimer, Shiffman, & Paty, 2005). One possibility suggested by the current work is that executive capacity mediates the effect of prior self-regulation on later alcohol consumption. Perhaps the ability to monitor alcohol intake while bearing in mind one's consumption limit—that is, the ability to maintain and update information in working memory—was disrupted by prior efforts at self-regulation, and this contributed to the limit violations. Future work on the applied behavioral consequences of reduced capacity for executive control represents a fruitful area for exploration.

Conclusion

The judicious use of executive control is one key to the remarkable diversity in human achievement, but executive control comes with a cost. The current findings indicate that executive control is costly in the sense that it depletes a limited internal resource. Future research that specifies the biochemical correlates and brain structures that underlie the resource will further refine the resource view. Nevertheless, the idea that executive control operates like a limited resource generated several novel predictions and findings, and chief among them was the pattern of poorer performance on putative executive control tasks after prior, unrelated efforts at executive control. It appears that exercising some of the most advanced abilities of the human mind causes temporary deficits in just those abilities.

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