

Research Report

Running on Empty

Neural Signals for Self-Control Failure

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ABSTRACT—Past research shows that self-control is limited and becomes depleted after initial exertions. This study examined the neural processes underlying self-control failure by testing whether controlled, effortful behavior impairs subsequent attempts at control by depleting the neural system associated with conflict monitoring. Subjects either watched an emotional movie normally or tried to suppress their emotions while watching the movie; they then completed an ostensibly unrelated Stroop task while electroencephalographic activity was recorded. The error-related negativity (ERN)—a waveform associated with activity in the anterior cingulate—was measured to determine whether prior regulatory exertion constrained the conflict-monitoring system. Compared with subjects in the control condition, those who suppressed their emotions performed worse on the Stroop task, and this deficit was mediated by weaker ERN signals. These results offer a neural account for the self-regulatory-strength model and demonstrate the utility of the social neuroscience approach.

Abstinence is as easy to me, as temperance would be difficult.

—Samuel Johnson, cited in Bartlett (2002, p. 326)

It sometimes seems that people's wish to control their own hearts, bodies, and minds is met by a frustrating degree of failure. Whether they want to be less sensitive, perform better in school, keep to a diet, or fulfill other well-intentioned New Year's resolutions, they find themselves falling short year after year. Like Johnson, many people find tempering their desires—or exercising the will—difficult. However, the ability to control and restrain impulses is one of the defining features of the human animal, and its failure is one of the central problems of human society (Baumeister, Heatherton, & Tice, 1994; Damasio, 1994).

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Self-control refers to the mental energy individuals use to regulate their own thoughts, emotions, and behaviors (Muraven & Baumeister, 2000). It relies on controlled processes that effortfully override urges, emotions, and automatic response tendencies. Self-control can be construed as a central volitional resource used to orchestrate all kinds of intentional behaviors, including temporarily committing something to memory (Engle, 2002), engaging in lawful behavior (Gottfredson & Hirschi, 1990), inhibiting inappropriate responses (von Hippel & Gon-salkorale, 2005), and regulating emotions (Gross, 2007). Self-control is supported by a neurally based executive-control system that allows one to detect and then choose between competing response tendencies (Ellis, Rothbart, & Posner, 2004). In the study reported here, we sought to gain a better understanding of self-control—and, more specifically, its failure. We wondered if self-control fails because of depletions in the neural system responsible for monitoring conflict and error.

SELF-CONTROL AS A LIMITED RESOURCE

Research shows that people have a limited amount of self-control, and that tasks requiring controlled, willful action quickly deplete this central resource. Exerting self-control on one task impairs performance on subsequent tasks requiring this same resource (Baumeister & Heatherton, 1996; Muraven & Baumeister, 2000; Muraven, Tice, & Baumeister, 1998). For instance, studies have shown that suppressing one's emotions or engaging in effortful intergroup interactions can deplete self-control on subsequent unrelated tasks, such as solving a difficult puzzle, holding onto a handgrip exerciser, or naming the color of printed words in a Stroop task (Muraven et al., 1998; Richeson & Shelton, 2003).

But why is self-control limited? How does engaging in controlled behavior impair the performance of subsequent behavior? At present, the field lacks a general framework for understanding why one act of volition depletes volitional power for a second unrelated act. Resource models of self-control, therefore, would benefit from a fine-grained analysis of the neural processes underlying self-control failure.

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DUAL-SYSTEM MODELS OF COGNITIVE CONTROL

In the current investigation, our starting point was cognitive and neuroscientific models of mental control, in which two complementary systems are thought to be necessary for control. In Wiener's (1948) cybernetic model, he defined *control* as involving one process to monitor when something shifts away from a criterion and a second process to return this something to criterion. Social psychologists have elaborated this dual-system structure, postulating, for example, *test* versus *operate* mechanisms (Carver & Scheier, 1981) or *monitoring* versus *operating* processes (Wegner, 1994). Similarly, neuroscientists have described cognitive control as relying on two separate neural systems. The first, described as a *conflict-monitoring* system (Botvinick, Braver, Barch, Carter, & Cohen, 2001) or an *error-detection* system (Holroyd & Coles, 2002), monitors ongoing behavior and is sensitive to discrepancies between intended and actual responses. When a discrepancy is detected, this information is passed to the second, *regulatory* system, which implements the desired response while suppressing the incompatible one. Neuroimaging studies have suggested that these systems are supported by the anterior cingulate cortex and the prefrontal cortex, respectively (e.g., Kerns et al., 2004).

In electroencephalographic (EEG) studies, activation of the conflict-monitoring/error-detection system is associated with a component of the event-related potential (ERP) called the error-related negativity (ERN; Falkenstein, Hohnsbein, Hoorman, Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ERN is a sharp negative voltage deflection that typically peaks within 80 ms after response and has been shown to originate from the dorsal anterior cingulate cortex (van Veen & Carter, 2002). Research suggests that the ERN reflects pre-conscious error monitoring related to an impending error (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001).

Self-control failures, therefore, may occur because of depletions of either the monitoring or the operating system. This study addressed the former possibility: We hypothesized that engaging in self-control impairs subsequent attempts at control by weakening the neurally based monitoring system, an effect that would be evident in the ERN.

OVERVIEW

We examined the role of internal monitoring in regulatory depletion and tested the hypothesis that the neural system for conflict or error detection is constrained after people exert self-control on a previous unrelated task. To deplete self-control, we had subjects suppress their emotions while watching an upsetting movie. All subjects then completed a second task that requires executive attention and is thought to be associated with more general self-regulation, the Stroop task (Ellis et al., 2004). We predicted that subjects who controlled their emotions would show poorer executive control and reduced conflict monitoring

compared with subjects who did not control their emotions. We further predicted that the deficits in executive control would be mediated by reduced neural activity in the monitoring system.

METHOD

Subjects and Design

Subjects were 40 right-handed students (31 females, 9 males; mean age = 20.79) from the University of Toronto Scarborough, Canada. Data from 7 subjects were excluded from all analyses because of extensive EEG artifacts ($n = 2$), equipment malfunction ($n = 1$), excessive error rates ($> 40\%$) on incongruent Stroop trials ($n = 3$), or outlying EEG scores ($n = 1$). In a between-subjects design, subjects were randomly assigned to one of two conditions: emotion suppression ($n = 15$) or no emotion suppression (control) ($n = 18$).

Procedure

Subjects were fitted with an electrode cap for EEG recording. All subjects saw the same two excerpts from the documentary movies *Mondo Cane* (Jacopetti, Cavara, & Prosperi, 1962) and *Africa Addio* (Rizzoli, Jacopetti, & Prosperi, 1966), which depict animals suffering and dying. Subjects in the emotion-suppression group were instructed to suppress all internal reactions to the movie and all external signs of their feelings. Subjects in the control group were instructed to simply watch the movie excerpts carefully. Following the 10-min movie, subjects completed a manipulation check and an ostensibly unrelated task—the Stroop task—during which the experimenter recorded continuous EEG activity.

Measures

Manipulation Check

To determine whether subjects in the emotion-suppression condition followed instructions, we presented subjects with two items: "During the film, I tried not to feel anything at all" and "During the film, I reacted completely spontaneously" (reverse-coded; $\alpha = .69$). Subjects indicated their agreement with these statements on a 9-point Likert scale.

Stroop Task

Performance on the color-naming Stroop task was the main behavioral dependent variable. Stimuli consisted of the words *red* and *green*, presented in either red or green font. Subjects responded to each stimulus by pressing one button if the font color was red and a second button if it was green. On each trial, a fixation cross ("+") appeared for 500 ms, after which the stimulus word appeared for 200 ms; the maximum time allowed for response was 1,500 ms. On congruent trials, a color word appeared in a color that matched its semantic meaning (e.g., "red" presented in red font); on incongruent trials, a color word appeared in a color that mismatched its semantic meaning (e.g., "red" presented in green font). There were 48 trials per block,

and each block contained 32 congruent and 16 incongruent trials. Following 1 practice block, subjects completed 18 experimental blocks. We calculated the mean reaction time (RT) for each trial type using trials with correct responses only.

Electrophysiological Recording and Processing

EEG was recorded from 64 sintered Ag/AgCl electrodes embedded in a stretch Lycra cap. EEG was digitized at 512 Hz using ASA acquisition hardware (Advanced Neuro Technology, Enschede, The Netherlands) with an average electrode reference and forehead ground. Frequencies below 1 Hz and above 15 Hz were digitally filtered. The signal was baseline-corrected by subtracting the average voltage during the period 400 to 50 ms before the key press. Any wave that exceeded the threshold values of $-70 \mu\text{V}$ and $+70 \mu\text{V}$ was automatically marked and rejected. We response-locked each participant's EEG signals to create separate individual averages for correct and incorrect trials and then grand-averaged these values across participants, but within condition (i.e., suppression, no suppression). The ERN was quantified as the peak minimum deflection between 20 ms before response and 120 ms after response at the central midline electrode (Cz).

RESULTS

Behavioral Measures

We examined responses to the manipulation check to determine whether subjects in the suppression condition attempted to regulate their emotions. A t test showed the expected main effect, $t(31) = 3.05$, $p_{\text{rep}} = .97$, $d = 1.10$, with the emotion-suppression group ($M = 5.03$, $SD = 1.69$) reporting more regulation than the control group ($M = 3.11$, $SD = 1.89$).

To correct for violations of normality, we log-transformed all Stroop RTs, but we present the untransformed means here for ease of interpretation. The Stroop RTs were analyzed using a 2 (condition: control vs. suppression) \times 2 (trial type: congruent vs. incongruent) mixed-model analysis of variance (ANOVA), with the last factor repeated. This analysis revealed a significant main effect for trial type, $F(1, 31) = 76.41$, $p_{\text{rep}} = .99$, $d = 3.14$, the classic Stroop interference effect (see Fig. 1a). The analysis also yielded the expected interaction between condition and trial type, $F(1, 31) = 6.76$, $p_{\text{rep}} = .94$, $d = 0.93$; although subjects in both conditions showed Stroop interference (both $F_s > 20.74$, $p_{\text{rep}}s = .99$), the effect was significantly larger for the emotion-suppression subjects.

Further analyses confirmed that these results do not simply reflect general fatigue. The main effect for condition was non-significant, $F(1, 31) = 1.08$, $p_{\text{rep}} = .64$, which suggests that the slowing effect in the suppression group did not generalize to both congruent and incongruent trials. Further, when we analyzed Stroop performance as a ratio score, $(RT_{\text{incongruent}} - RT_{\text{congruent}}) / (RT_{\text{incongruent}} + RT_{\text{congruent}})$, a significant condition effect, $F(1, 32) = 6.88$, $p_{\text{rep}} = .94$, confirmed our first analysis and suggested that the Stroop effect was larger in the suppression

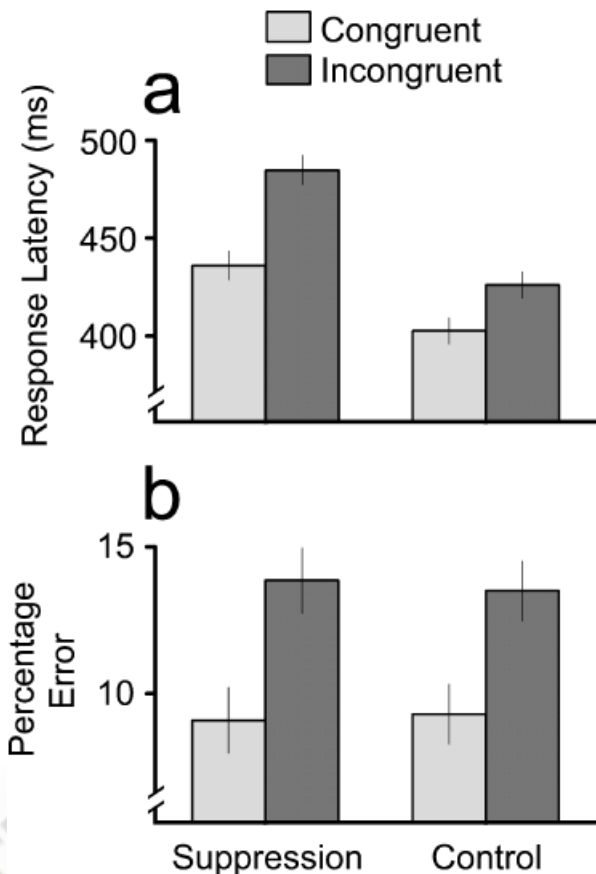


Fig. 1. Stroop response latency (a) and error rate (b) as a function of trial type and condition. Error bars represent standard errors of the mean difference.

group than in the control group. These results suggest that subjects who suppressed their emotions had a more difficult time maintaining executive control in an unrelated task than control subjects did. The error rates, illustrated in Figure 1b, showed the typical Stroop interference effect, $F(1, 31) = 35.59$, $p_{\text{rep}} = .99$, $d = 2.15$, but failed to reveal a significant condition effect or interaction, $F_s < 1$, n.s.

ERN

Analysis of the neural waveforms supported our prediction that the conflict-monitoring/error-detection system would be weakened by the exercise of self-control. Individuals who suppressed their emotions during the movie showed attenuated ERNs relative to control subjects (see Fig. 2).

We ran a 2 (condition: suppression vs. control) \times 2 (response: correct vs. error) mixed-model ANOVA on ERN minimum amplitude, with the last factor repeated. The analysis revealed a main effect for response, $F(1, 31) = 13.66$, $p_{\text{rep}} = .99$, $d = 1.33$, with errors generating larger negative deflections ($M = -2.19$, $SD = 1.51$) than correct responses ($M = -1.02$, $SD = 1.45$), a pattern typical of the ERN. This effect was qualified by an interaction between condition and response, $F(1, 31) = 3.89$, $p_{\text{rep}} =$

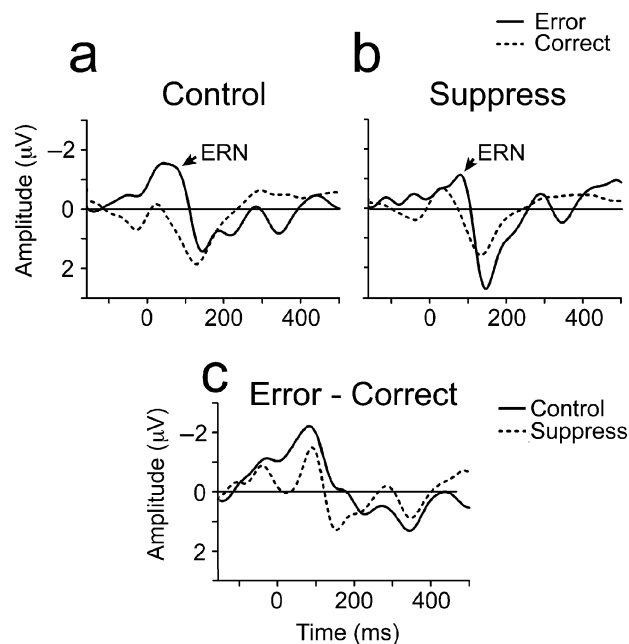


Fig. 2. Response-locked event-related potential waveforms at the Cz electrode. The upper graphs show average waveforms for correct versus error trials, separately for the (a) control and (b) emotion-suppression conditions. The ERN appears as a negative wave peaking at about 70 ms. The bottom graph (c) shows the average difference waveform (error trials minus correct trials) in each condition. Zero indicates the time of key press.

.88, $d = 0.71$. A simple-effects test showed that subjects in the control group had large ERNs, $F(1, 31) = 17.67$, $p_{\text{rep}} = .99$, $d = 1.51$, with larger negative deflections on error trials ($M = -2.42$, $SD = 1.48$) than on correct trials ($M = -0.85$, $SD = 1.06$). Subjects in the emotion-suppression group showed much smaller ERNs, $F(1, 31) = 1.36$, n.s., and their ERNs did not differ between error trials ($M = -1.69$, $SD = 1.52$) and correct trials ($M = -1.23$, $SD = 1.44$). The nonsignificant ERN in this group supports our hypothesis, suggesting that the discrepancy between intended and actual behavior may not have been preconsciously detected after people engaged in controlled, effortful behavior.

Mediation of Stroop Interference

Is self-control failure mediated by weak error monitoring? To test for this possibility, we computed a series of regression equations relating suppression (the independent variable; dummy-coded), ERN (the potential mediator; $ERN_{\text{correct}} - ERN_{\text{error}}$), and Stroop interference (the dependent variable; log of $RT_{\text{incongruent}} - RT_{\text{congruent}}$). The results of this analysis are depicted in Figure 3.

As reported earlier, suppression increased Stroop interference, $\beta = .32$, $t(31) = 1.90$, $p_{\text{rep}} = .86$, $d = 0.68$, and weakened ERN amplitude, $\beta = -.33$, $t(31) = -1.97$, $p_{\text{rep}} = .88$, $d = 0.71$. An additional regression established that the ERN predicted Stroop interference, $\beta = -.32$, $t(31) = -1.83$, $p_{\text{rep}} = .85$, $d = 0.66$. When ERN amplitude was included in the regression, suppression no longer significantly predicted Stroop interfer-

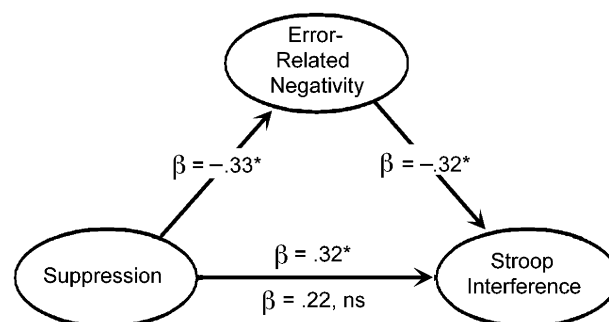


Fig. 3. Results of regression analyses testing the error-related negativity as a mediator of the effects of emotion suppression on Stroop interference. Asterisks indicate coefficients significantly different from zero, $p_{\text{rep}} > .85$. When the mediator is included, the initial beta weight changes from $\beta = .32$ to $\beta = .22$.

ence, $\beta = .22$, $t(31) = 1.25$, $p_{\text{rep}} = .71$, $d = 0.45$. The significance of this mediation effect was tested using the $z' = \alpha\beta/\sigma_{\alpha\beta}$ method described by MacKinnon, Lockwood, Hoffman, West, and Sheets (2002). In this case, z' was equal to 1.45 ($p_{\text{rep}} = .88$),¹ suggesting that changes in the ERN accounted for the effects of suppression on Stroop performance. This analysis supports our hypothesis that engaging in controlled, effortful behavior impairs subsequent attempts at control by weakening the neurally based monitoring system.

Our hypothesis centered on the conflict-monitoring/error-detection system, but not the ERN per se. Although the ERN is an index of this system, the two are not isomorphic—error monitoring occurs whether or not an error is made. Thus, although error trials are the best time to measure this neural system's ongoing activity (at least with ERPs), it is not the case that the system is active only during error trials. Our results showed that the ERN (calculated *with* error trials) predicted Stroop performance (calculated *without* error trials), $r = -.39$, $p_{\text{rep}} = .92$, $d = 0.85$, and suggest that a system responsible for error or conflict detection can affect attentional control even when a correct response is made.

DISCUSSION

According to the self-regulatory-strength model, the ability to move oneself toward a desired state relies on a limited, easily exhausted resource. When this resource is depleted, the likelihood of self-control failure increases. The current study suggests an account for how this happens: After people exert control, their neural systems are less responsive to a mismatch between their actions and their goals. Our results showed that the neural mechanisms for monitoring conflicts and errors were weakened among subjects who exerted themselves on an emotion-suppression task. So people whose self-control resources

¹As discussed by MacKinnon et al. (2002), z' uses a nonnormal distribution. Thus, critical values differ from those associated with typical z tests. Critical values are available on the Web at <http://www.public.asu.edu/~davidpm/ripl/methods.htm>.

are depleted—whether from fending off thoughts of food all day (Vohs & Heatherton, 2000) or from coping with a stigmatized social identity (Inzlicht, McKay, & Aronson, 2006)—have difficulty controlling themselves because their neurally based conflict-monitoring/error-detection system has reduced their ability to monitor losses of control.

In finding that controlling oneself for a relatively brief period impairs error monitoring, this study has extended research in both social psychology and neurophysiology. Most important, it suggests a neuroscientifically informed account of how self-control is constrained by previous acts of control, thereby extending current work on the resource model of control (see also Richeson et al., 2003). This study also shows that mental fatigue—operationalized in the neurophysiological literature as working on the same task for hours on end or after extended periods of wakefulness (Boksem, Meijman, & Lorist, 2006; Scheffers, Humphrey, Stanny, Kramer, & Coles, 1999)—can occur relatively quickly (e.g., after a 10-min movie) and affect tasks unrelated to the depleting activity.

Acknowledgments—This research was supported by a Spencer Foundation/National Academy of Education fellowship and by a Social Sciences and Humanities Research Council grant to Michael Inzlicht. We give special thanks to David Amodio, Dominic Packer, Jennifer Mangels, Belle Derks, Bill von Hippel, and Naomi Sarah Ball.

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(RECEIVED; REVISION ACCEPTED 2/16/07;
FINAL MATERIALS RECEIVED 3/6/07)

