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Reducing self-control depletion effects through enhanced sensitivity to implementation: Evidence from fMRI and behavioral studies

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Abstract

Research suggests self-control relies on a limited set of resources that can be diminished by use. Recent theories posit that there are two stages of self-control: recognizing the need for control and implementing controlled responses. We conducted a functional magnetic resonance imaging experiment and an intervention experiment to investigate whether one or both stages were affected by the prior exercise of self-control. Results from both experiments indicated that only the implementation stage was affected. Further, we demonstrate that self-control can be increased by an intervention designed to boost implementation, as opposed to the recognition of the need to control one's responses.

Keywords: Regulatory resource depletion; Self-control; fMRI; Decision neuroscience

The exercise of self-control is a crucial element of human behavior, particularly as it pertains to judicious consumption. Choices regarding whether, what, and how much one consumes bear on the well-being of individuals and society. Opting to consume unhealthy foods, smoke, or drink alcohol can adversely impact individual consumers, and can also impose a negative externality on others through effects such as increased health care costs. Moreover, knowing the nature and structure of self-control is essential for building an integrative theory of one of humankind's greatest strengths. In short, understanding how self-control operates is an important practical and theoretical enterprise (Hagger, Wood, Stiff, & Chatzisarantis, 2010; Hofmann, Strack, & Deutsch, 2008).

Psychology and marketing scholars have established that the ability to engage in self-control is contingent on the availability of particular resources (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Vohs & Heatherton, 2000; Wan, Rucker, Tormala, & Clarkson, 2010). This limited resource model of self-control claims that people possess an inner reservoir of resources that become depleted when people engage in a prior task that requires self-control.

In order to investigate the nature of self-regulatory resource depletion, we draw from a recent two-stage model of self-control failure (Myrseth & Fishbach, 2009). According to this model, self-control failure can follow from impairments in one or both of two stages. One stage involves recognizing the conflict between succumbing to temptation versus achieving a longer-term goal. A second stage involves implementing actions to avoid succumbing to temptation.

The limited resource model of self-control has been mute about the operations that self-regulatory resource depletion impairs. Based on the two-stage model, it is possible that depletion affects the recognition that a self-control dilemma

Abbreviations: ACC, anterior cingulate cortex; BA, Brodmann Area; DFMC, dorsal frontal median cortex; DLPFC, dorsolateral prefrontal cortex; EEG, electroencephalogram; fMRI, functional magnetic resonance imaging; rMFG, right middle frontal gyrus.

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exists, the implementation of regulated responses, or both (Inzlicht & Gutsell, 2007; Richeson et al., 2003). We used fMRI to identify the stage at which self-regulatory resource depletion takes its toll. This approach holds considerable promise to improve the field's understanding of consumer behavior in general (Childers & Jiang, 2008; Park, 2008) and self-control in particular (Litt, Pirouz, & Shiv, 2012). Since conflict recognition and the implementation of regulated responses have been associated with different parts of the brain, such a decision neuroscience approach was particularly appropriate to answer our question (Dietvorst et al., 2009; Hedgcock & Rao, 2009; Reimann, Zaichkowsky, Neuhaus, & Weber, 2010; Yoon, Gutchess, Feinberg, & Polk, 2006).

Self-control as a limited resource

Prior research has established that the capacity to engage in self-control depends on a set of limited resources. Actions that require self-control, such as stifling emotions, fixating attention, making decisions, or overcoming untoward desires, require the deployment of these resources and appear to reduce or deplete them (Muraven & Baumeister, 2000). When self-control resources are depleted, people's ability to exercise self-control during a subsequent task often suffers. For instance, behaviors that require the deliberate regulation of responses deplete regulatory resources and cause unplanned spending (Vohs & Faber, 2007) and overeating among dieters (Vohs & Heatherton, 2000). Further, compared to people who have not exerted self-control, people who have recently exercised self-control display less physical stamina (Vohs et al., 2008), drink more beer (Muraven, Collins, & Nienhaus, 2002), underperform on logic and intelligence tasks (Schmeichel, Vohs, & Baumeister, 2003), and exhibit greater racial bias (Richeson et al., 2003). Although the behavioral consequences of the depletion of self-control resources are well-documented (for a summary, see Baumeister, Vohs, & Tice, 2007), the mechanisms that account for these effects are not well understood (Hagger et al., 2010, Johnson, 2008). Several have been suggested. Memory deficits (Richards & Gross, 2000), narrowed attention (Muraven & Baumeister, 2000), reduced motivation (Wan & Sternthal, 2008), and reduced glucose levels (Gailliot et al., 2007) have been identified as potential contributing factors that explain why earlier acts of self-control produce later decrements in self-control.

We propose a new approach to understanding what changes occur in people when they engage in self-regulation and how these changes put them at risk for subsequent self-regulation failure. We adopted a two-stage model to study the operations involved in self-control and determine where depleted self-regulatory resources have their effects. To do so, we used fMRI technology to study the neural correlates of self-regulation resource depletion (Study 1). The findings from our fMRI study were used to design an intervention that improved self-control in depleted participants (Study 2).

Two-stage models of self-control

Self-control has been conceptualized as a two-stage process that involves conflict identification and the implementation of regulated behavior (Carver & Scheier, 1990; Myrseth & Fishbach, 2009; Strack & Deutsch, 2004). According to these approaches, self-control is needed when people face a dilemma in which there are conflicting goals, such as between the immediate rewards of indulging in a snack versus the long-term rewards of eating in a healthy fashion. Successful self-control can only occur if people first identify the conflict and then modify their behavior. For instance, dieters will only avoid an unhealthy snack if they (1) identify that there is a conflict between their immediate desire for the snack and their desire to lose weight, and then (2) implement a modified behavior such as eating a healthy snack or physically removing themselves from proximity to the tempting snacks.

Neuroscientific studies using similar two-stage models to study executive control tasks (i.e., tasks that require the resolution of conflict) have determined that the two stages are dissociable (MacDonald, Cohen, Stenger, & Carter, 2000). Conflict identification is associated with activity in the anterior cingulate cortex (ACC) (Kerns et al., 2004; MacDonald et al., 2000; van Veen & Carter, 2002) whereas implementation of executive control is associated with activity in the dorsolateral prefrontal cortex (DLPFC) (Kawashima et al., 1996; MacDonald et al., 2000) and implementation of motor control is associated with activity in the dorsal frontal median cortex (DFMC) (Brass & Haggard, 2007). When confronted with an initial task that requires self-control, people must first identify that a conflict exists, a process associated with increased activity in the ACC. Once conflict is identified, regulated responses need to be implemented, a process associated with increased activity in the DLPFC.[1]

Our primary interest is in what happens next. Once people's regulatory resources have been depleted and they are confronted with a new decision that has conflicting goals, why might the self-control system fail? Based on two-stage models, the premise that either (or both) stages require self-regulatory resources that can be depleted, and the premise that the elements of conflict identification and implementation of control are dissociable, there are three possibilities.

First, the initial self-control task might impair conflict *identification* abilities but leave intact the ability to implement controlled behaviors. For instance, dieters could fail at the conflict identification stage by mindlessly picking up and eating a snack. In this case, we would expect to see reduced activity in the ACC, but not in the DLPFC, during the second task. Inzlicht and Gutsell (2007) have found support for this notion.

Second, the initial task might impair the *implementation of control* but leave intact conflict identification abilities. For instance, dieters could fail at the implementation stage by indulging in a snack even after recognizing the conflict between

[1] In the interest of brevity, and consistent with prior executive control research (e.g., Inzlicht & Gutsell, 2007, MacDonald et al., 2000, Richeson et al., 2003) we focus our discussion on executive control and the ACC and DLPFC, not motor control and the DFMC.

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immediate gratification and future health consequences. In this case, we would expect to see reduced activity in the DLPFC, but not the ACC, during the second task. Richeson et al. (2003) speculated (but did not demonstrate) that depleted participants might have reduced activity in the right middle frontal gyrus (rMFG, which is located in the right DLPFC). Indirect support comes from Shackman, McMenamin, Maxwell, Greischar, and Davidson (2009), who reported that activity in the rMFG is correlated with self-reported measures of behavioral inhibition and Kerns et al. (2004) who found activity in the rMFG was correlated with behavioral adjustments during a Stroop color naming task.[2]

Third, it is possible that both conflict identification and implementation of control are diminished by the first task. For instance, dieters could sometimes fail at the conflict identification stage by mindlessly picking up and eating a snack and sometimes fail at the implementation stage by indulging in a snack even after recognizing conflict. In this case, there ought to be reduced activity in the DLPFC *and* in the ACC during the second task.

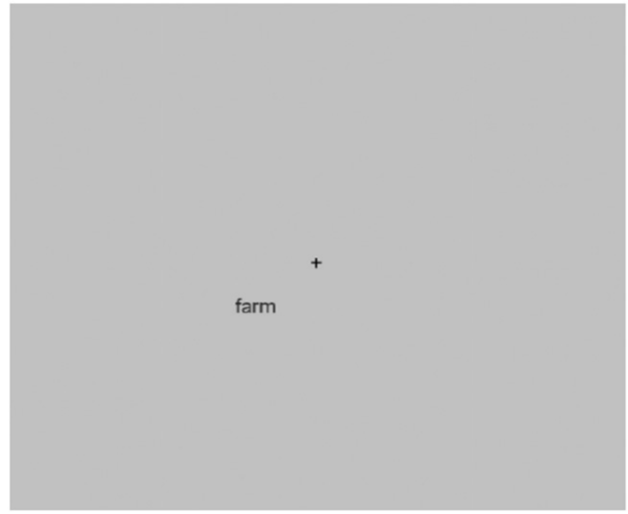

Fig. 1. Attention-control task stimuli. A fixation point was located in the center of the screen. Words were presented just below the fixation point and either to the left or right of the fixation point. Forty-six words were displayed per block for 4.5–7.5 seconds each. The total task time for each block was 4.6 minutes.

Study 1: an fMRI investigation of the neural correlates of depletion

The fMRI study was designed to help distinguish among three possible outcomes suggested by the two-stage model discussed earlier. Participants performed an initial task that taxed their self-control resources, or they performed a similar task that did not tax their self-control resources. Then they performed a subsequent choice task during which the potential effects of regulatory resource depletion were assessed using behavioral and brain imaging measures. The choice task was employed as it satisfied two necessary criteria for an fMRI study of regulatory resource depletion. First, it allowed us to expose participants to multiple repeated measurements. Second, prior studies have demonstrated that these kinds of choice decisions require self-control (Bruyneel, Dewitte, Vohs, & Warlop, 2006; Vohs et al., 2008; Wang, Novemsky, Dhar, & Baumeister, 2010).

Our self-control manipulation used a common task that has been successfully used in prior depletion research (Schmeichel et al., 2003; Vohs & Faber, 2007). All participants were instructed to fix their attention on a small cross in the middle of a computer screen while words periodically appeared onscreen (Fig. 1). Participants in the *attention demanding* condition were told to ignore the words on the screen. If they found themselves attending to them, they were instructed to revert their eyes immediately back to the fixation cross. Participants in the *neutral* condition were told that the words could be looked at or ignored.[3]

Participants

Seventeen adults participated in exchange for $95 each. One participant's data were unusable because of inaccurate data collection, leaving usable data from 16 participants (9 female, M_{age}=27.4, SD=9.0). All participants were right-handed, healthy, native English speakers with normal or corrected-to-normal vision. Participants were free of neurological and psychiatric history and were screened for safety in a magnetic resonance imaging study.

Design and procedures

Participants attended two fMRI sessions. At the first fMRI session, participants were randomly assigned to either the attention demanding or neutral condition. At the second fMRI session, conducted approximately two weeks later, participants who had earlier been assigned to the attention demanding condition were now assigned to the neutral condition, and vice versa. Each fMRI session involved four distinct blocks of tasks. Participants took a short break between blocks. Attention was manipulated during blocks 1 and 3 through the employment of appropriate instructions, though the stimuli were identical. In

[2] There is an ongoing discussion in the literature about processing differences between the right and left hemisphere of the prefrontal cortex. A recent meta-analysis (Laird et al., 2011) found a trend towards hemispheric differences that might be related to verbal and visual spatial processing differences. Given the current state of knowledge, it is not possible to specify whether differences should occur in one or both hemispheres of the DLPFC.

[3] We conducted two pretests to ensure that our self-control manipulation would yield differences in self-regulation when participants were exposed to measures of self-control and our repeated choice stimuli. Consistent with expectations, our first pretest showed participants in the attention demanding condition made faster decisions, had impaired Stroop task performance, and had stronger preferences for indulgent snacks than participants in the neutral condition. Our second pretest showed that participants in the attention demanding condition made faster decisions during the choice task than participants in the neutral condition. Details of these pretests are available in the appendix.

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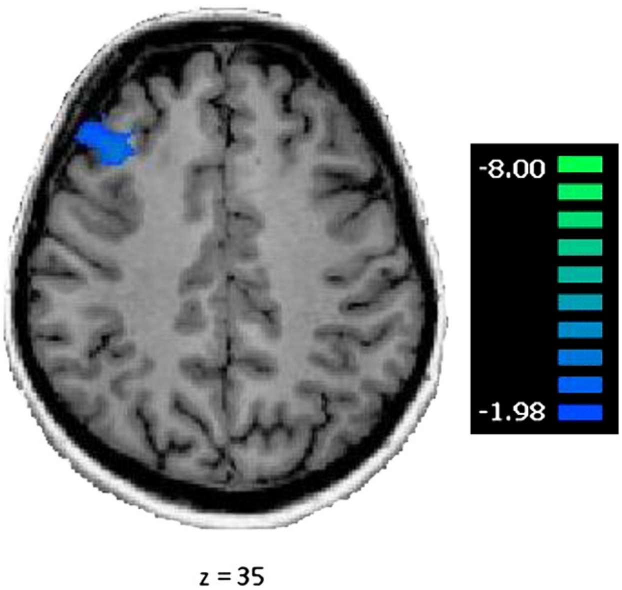

Fig. 2. Neural activation during the choice task following the performance of the attention-control task. rMFG is less active during the choice task after participants performed the attention-demanding versus neutral task (cluster-level significance $p<.05$).

blocks 2 and 4, participants performed a choice task. Participants first read a description of the choice scenario and then saw a list of options. Participants were told to select their most preferred option. Participants responded with their right hand using a keypad. Stimuli were projected on a screen outside of the scanner that participants viewed via a mirror located above their eyes.

After each fMRI session was completed, participants responded to a questionnaire to check the effectiveness of the manipulation. The questionnaire asked them to briefly describe the instructions for the attention-control task, which all participants correctly recalled. They then responded to a manipulation check item ("How mentally demanding was the task?") by circling a number from 1 ("very easy") to 7 ("very hard").

Analysis and results

MRI data acquisition and preprocessing

Imaging was conducted on a 3 Tesla, Siemens Trio whole body scanner with a standard CP head coil. Functional scans using an EPI sequence (35 slices, TE=28, TR=2000 ms, flip angle=90 degrees; 3.5 mm^2×2.5 mm slices with a 1.0 mm skip between slices, TR=2000 ms) were obtained in an oblique orientation of 20 degrees to the anterior commissure/posterior commissure line. The 2.5 mm slice thickness and slice orientation help minimize susceptibility problems in ventral prefrontal cortex regions. Structural scans for each participant were performed using a T1-weighted MPRAGE sequence (176 slices, 1 mm^3).

Image analyses and preprocessing were performed using Brainvoyager QX (Version 1.10, Brain Innovation, the Netherlands). Functional scans were preprocessed as follows: three-dimensional motion correction, slice scan time correction, spatial smoothing, and temporal data smoothing. No participant had greater than one voxel movement in any direction. Spatial smoothing was performed using a 4-mm full-width, half maximum Gaussian kernel. Temporal smoothing used a high-pass filter (cutoff frequency=3 cycles per functional run) to remove low-frequency drift or oscillations. Participants' anatomical images were normalized to the Talairach and Tournoux brain template. Functional volumes were then standardized using the transformation parameters from the anatomical images. The first three volumes of each functional scan were discarded to minimize problems with T1 saturation effects.

fMRI statistical analyses

Statistical analyses were performed in two stages. First, blood oxygen level dependent (BOLD) activity associated with the performance of the task was assessed for each voxel using the general linear model (GLM) in Brainvoyager QX. Unique predictors were created for each part of the decision task: 60 second fixation (Fix1), 2 second inter-choice fixation (Fix2), choice description (Desc), choice (Choice), post choice (Post), instructions (Instruct), and attention task (Attn). The choice description, choice and attention tasks were further defined based on whether they occurred during the attention condition (AC) or during the neutral condition (E). The attention task was defined further based on whether the stimuli moved (M) or did not move (N) during that trial. This lead to a total of 12 predictors (Fix1, Fix2, DescAC, DescE, ChoiceAC, ChoiceE, Post, Instruct, AttnACM, AttnEM, AttnACN, AttnEN) with Fix1 defined as the baseline condition. The onset of each predictor was convolved with a two gamma hemodynamic response function to identify voxels with blood flow that correlated with the predictors. Consistent with previous research (Dietvorst et al., 2009; Yoon et al., 2006), we used a mask to restrict analysis to specific anatomical regions. These regions included Brodmann Areas (BAs) 9, 24, and 32, areas that have previously been implicated in executive control Kerns et al., 2004; MacDonald et al., 2000).

Manipulation checks

A paired *t*-test confirmed that the attention demanding version of the task was perceived as more demanding than the neutral version ($M_{\text{attention}}=2.72$, SD=2.00>$M_{\text{neutral}}=1.69$, SD=1.20, $t(15)=2.49$, $p=0.025$). Further, and consistent with our pretest based expectations, participants who had first performed the attention demanding version of the task made faster decisions in the subsequent choice task ($M=9503$ ms, SD=4378) than those who had first performed the neutral version of the task ($M=10121$ ms, SD=4558; $F(1, 642)=4.34$, $p=0.0376$).

An analysis of the brain activity during the first task confirmed that the attention demanding version of the task activated areas of the brain associated with executive control more than the neutral version of the task. Beta values from the first stage analysis described above were used in a second stage analysis of variance (ANOVA) in which participants were treated as a random effect and order (whether participants experienced the attention demanding or neutral condition first) was treated as a between-participants factor. Analysis continued with a contrast of the attention demanding conditions

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versus the neutral conditions. We set the voxel-level threshold to $p<0.05$ (uncorrected) and ran 1000 iterations of Monte Carlo simulations to estimate a cluster size threshold with a false positive rate of 5%. This estimation found a minimum cluster size of 324 mm^3. Regions of interest are reported in Table 1 if they exceeded a probability threshold of $p<0.05$ and a minimum contiguous cluster size of 324 mm^3.

As predicted, brain activity during the attention task varied as a function of the condition to which participants were assigned. When participants were in the attention demanding condition, they displayed greater activity in the right and left DLPFC (BA 9) and the ACC (BAs 32, 24, 9) (Table 1) relative to when they were in the neutral condition. These brain regions have been associated with executive control in prior research (Kerns et al., 2004; MacDonald et al., 2000). This result, combined with our self-report manipulation check, is consistent with our prediction that the attention manipulation would increase executive control processing.

Depletion imaging results

As predicted, there was an effect of attention control on subsequent brain activation. Participants displayed less activation during the second task in the rMFG (BA 9), which is located in the right DLPFC, when their resources had been depleted relative to when their resources had not been depleted (Table 2). No other areas showed significant differences (Fig. 2).

This finding is consistent with the argument that self-regulatory resource depletion impairs the subsequent ability to implement controlled behavior (Richeson et al., 2003). That activity in the ACC did not show significant differences as a function of condition is inconsistent with the theory that self-regulatory resource depletion impairs the ability to identify conflict.

Discussion

We set out to test a two-stage model of self-control using fMRI methods to help distinguish whether self-regulation failure after prior self-regulation likely is due to the failure to recognize a self-control conflict or the failure to implement regulated responses. Our results provide evidence about the neural correlates of regulatory resource depletion. The rMFG is less active when participants are depleted relative to when they are not depleted, which is consistent with a diminished capacity to implement control. We did not see evidence that blood flow to the ACC, a brain region associated with conflict identification, changed with condition. This (null) result is inconsistent with the idea that self-regulatory resource depletion affects people's ability to identify possible conflicts between short- and long-term goals.

If indeed, the failure to implement control (and not the failure to identify conflict) is the source of self-control failure, then providing people with tools to enhance their implementation ability ought to reduce self-control failure. In other words, people who experience self-control failure following the exercise of self-control ought to be less prone to such failure if an intervention forces them to focus on ways in which they might implement self-control. Further, since our fMRI study indicates that conflict identification failures do not account for self-control failure, an intervention designed to improve conflict identification ought not to yield an enhancement in self-control. To assess whether interventions along these lines would yield the predicted effects, we conducted a behavioral experiment described next.

Study 2: Investigating mechanisms to improve self-control

We conducted an experiment to assess whether alerting participants to the need to implement controlled processes, or to the idea that temptations might conflict with other goals, would affect their ability to exert self-control relative to participants who did not receive these instructions. On the basis of Study 1's results, we predicted that interventions designed to improve the implementation of control would aid self-control more than no interventions and interventions designed to improve conflict identification. The latter condition was predicted to not differ from the no intervention condition, in line with the implications of Study 1's results.

Design

We employed a three-cell, between subjects design. In all conditions, participants first performed a resource-depleting task. Participants were told to either focus on *implementation* of goals, *conflict* between short- and long-run consequences of their choices, or were provided no instructions (see Gollwitzer & Kinney, 1989 for similar manipulations). Preferences for healthy and unhealthy foods were our measure of self-control (Shiv & Fedorikhin, 1999).

Table 1
Voxels with statistically significant activation differences in attention-demanding versus neutral tasks.

Location	Hemisphere	Brodmann area	Talairach coordinates	Average *t*-Stat	Cluster size (voxels)
Middle frontal gyrus/superior frontal gyrus	R	9	25, 54, 32	4.821	1286
Anterior cingulate		32/24	5.5, 32, 23	4.598	780
Anterior cingulate/middle frontal gyrus		32/9	−8.5, 37, 24	4.991	2249
Superior frontal gyrus	L	9	−28, 48, 30	5.166	1809

Note: All x, y and z coordinates denote center of gravity for each cluster in Talairach coordinates.
Areas of statistically significant activation differences for the contrast of attention-demanding versus neutral. ($n=16$, random effects ANOVA, $p<.05$, Monte Carlo Estimation Minimum Cluster Size>324 mm^3, $\alpha<.05$).

Procedures and stimuli

The study was conducted on the campus of a large Midwestern University. Eighty adults were recruited as they exited the University's recreational facility (29 women, M_{age}= 26.9, *SD*=11.9).

Participants first indicated preferences for a healthy snack and beverage as well as a relatively unhealthy snack and beverage. The healthy options were drawn from a set of alternatives including: a Clif Bar, a Powerbar, Propel Zero, and calorie free Vitamin Water. The unhealthy options were drawn from a set of alternatives including: a Snickers bar, a MilkyWay bar, Coca-Cola and Pepsi. Participants' preferences for snacks and beverages were recorded on a visual analog scale anchored at "I definitely would not select this snack (drink)" and "I definitely would select this snack (drink)".

Next, all participants engaged in a regulatory resource depletion task. Consistent with a procedure employed by Baumeister et al. (1998), participants were asked to cross out every "e" on a page taken from an advanced statistics text. Then they turned the page to find more text from the same textbook, but were told to follow different and more complicated rules. They were told to "Cross out every letter 'e' unless it is adjacent to another vowel or one letter removed from another vowel." This task required participants to overcome the established habit to cross out every "e".

Next, participants were exposed to the intervention manipulation. In the "Implementation Intervention" condition, participants were instructed to "…be mindful of the behaviors that you will need to do in order to reach your health goals. Please write an example of these behaviors below:", before responding to dependent measures. In the "Conflict Intervention" condition, participants were instructed to "…be mindful of the conflict between immediate desires and future health consequences of each option. Please write an example of this conflict below:", before responding to dependent measures. In the "No Intervention" condition, participants received no goal-related instructions prior to responding to the dependent variables.

Participants again indicated their preferences for relatively healthy and unhealthy snacks and beverages. The second set of healthy options for those who had initially been exposed to the Clif Bar and Propel Zero were a Powerbar and calorie free Vitamin Water and vice versa for participants who had been exposed to the other set of products. The second set of unhealthy options for participants who had been initially exposed to a Snickers bar and Coca-Cola were a MilkyWay bar and Pepsi and vice versa for participants who had been exposed to the other set of products. Last, as compensation, participants were allowed to select a snack and beverage.

Results

We predicted that regulatory resource depletion would make unhealthy snacks relatively more attractive than healthy snacks. However, based on the findings from our first study, we expected that effect to be attenuated among participants who had been exposed to an implementation intervention, but not among participants exposed to a conflict intervention.

To test this prediction, we first calculated the difference between preferences for healthy and unhealthy options both before and after the manipulations. The initial differences between the preferences for the healthy versus the unhealthy options were coded as the pre-intervention measure of preference. A positive value reflected a preference for the unhealthy option. For instance, if a participant marked the scale at 90 mm for a MilkyWay candy bar and at 80 mm for PowerBar, the difference score would be +10 mm. Next, we calculated the difference between ratings for the products after participants had completed the resource depletion task and intervention manipulation. The difference between the post- and pre-intervention differences measured changes in preference for unhealthy options relative to healthy options and served as our dependent variable. A positive value reflected an increased preference for the unhealthy option.

We created a preference index by adding the two difference scores (for beverages and snack bars) (r=.19, p=0.05). This index was analyzed using an ANOVA with condition, order, and their interaction as independent variables. The main effect for intervention condition was significant ($F(2, 74)=5.41$, $p=0.006$), indicating that the interventions affected preferences for healthy and unhealthy products.

Planned contrasts showed the predicted significant difference between no intervention and implementation intervention conditions (M=12.8, SD=73.9 vs. −32.5, SD=65.8; $F(1, 74)=10.78$, $p=0.0016$). Moreover, the predicted difference between the implementation intervention and conflict interventions was significant (M=−32.5, SD=65.8 vs. M=−4.8, SD=52.5; $F(1, 74)=3.05$, one-tailed $p=0.042$). Also as expected, the difference between the no intervention and conflict interventions was not significant (M=12.8, SD=73.9 vs. −4.8, SD=52.5; $F(1, 74)=1.90$, $p=0.172$). Overall, our hypothesis that implementation-focused interventions can reduce the effects of regulatory resource depletion received empirical support.

Discussion

We tested regulatory resource depleted participants' preferences for healthy and unhealthy snacks after receiving no intervention or interventions that were designed to increase implementation of control or conflict identification. As predicted, we found that participants exposed to the implementation intervention condition had relatively higher preferences for healthy snacks relative to participants exposed to the no intervention condition and the conflict intervention condition. The latter two conditions were not significantly different from each other. These results are consistent with the findings of our earlier fMRI study, which together provide support for the theory that implementation resources are depleted by an earlier depletion task.

General discussion

Modern life requires that people engage in self-control repeatedly through the course of the day. The consequent depletion of self-regulatory resources might explain the frequent occurrence of self-control failure. Failure to exercise self-control is a widespread problem that has deleterious effects on individuals and society. To uncover a mechanism that accounts for self-control failure, therefore, is an important task that can enhance the prediction of when self-control may fail and can assist in the design of interventions to reduce the incidence of such self-control failures (cf. Hagger et al., 2010; Thaler & Sunstein, 2009). This has been the goal of our research inquiry. We now turn to a discussion of the implications of our findings.

Theoretical implications

The finding that participants displayed diminished activity in the rMFG when their regulatory resources were diminished during the choice task (relative to when their resources were intact) speaks to the neural underpinnings of regulatory resource depletion. The rMFG has been implicated in key self-control processes including the implementation of top-down control (MacDonald et al., 2000), the regulation of valuation signals during decisions about healthy versus tasty foods (Hare, Camerer, & Rangel, 2009), and self-reported measures of behavioral inhibition (Shackman et al., 2009). Reduced rMFG activity might help explain why people who exercise self-control are later prone to self-control failure. Our findings are consistent with the theory that the prior exercise of self-control reduces the subsequent ability to engage in self-control, not because people lack the capacity to identify the existence of a conflict but because they lack the capacity to implement self-control. The subsequent behavioral study in which we manipulate different interventions complements the findings of the brain imaging work.

Practical implications

Self-control failures cause many of the problems that affect consumers. But, it is difficult to recommend appropriate interventions that could enhance self-control when the underlying causes of these failures are not well understood. If, as in the case of alcohol consumption, regulatory resource depletion affects consumers' ability to monitor their behavior (Hull, 1981), then interventions should focus on increasing consumers' ability to recognize conflict. Interventions that encourage consumers to pay for purchases with cash rather than credit cards might decrease impulsive purchasing by increasing conflict awareness (Raghubir & Srivastava, 2008).

However, our results suggest that interventions should focus on consumers' capacity to implement control. For instance, dieters sometimes offer to pay a friend if they violate their diet regimen and thus fail to implement control. The website stickK.com has formalized a procedure to foster the implementation of control by offering people who specify a goal the opportunity to send friends and acquaintances emails about their progress and suffer monetary consequences (via donations to charitable causes) if they do not achieve their goal. These types of actions likely increase the capacity to implement control since a small indulgence results in substantial monetary and social costs, in addition to increasing the distance to the goal. Our intervention study is consistent with this notion, that implementation interventions can increase self-control after regulatory resource depletion.

Limitations

Neuroscientific studies have shortcomings that ought to be acknowledged. First, sample sizes tend to be small, because data collection is extraordinarily expensive (often over $500 per subject) and time consuming. In our case, our sample size is consistent with other similar neuromarketing studies (e.g., Dietvorst et al., 2009; Hedgcock & Rao, 2009; Reimann et al., 2010; Yoon et al., 2006) and yields statistically significant results, hence statistical power is not an issue. Second, the study setting is intrusive and experimental tasks are quite divorced from reality. This concern is a necessary evil associated with the research method. It is impossible to access neural activity in an unobtrusive manner. Third, researchers should use care when inferring cognitive processes based on brain imaging findings because of the possibility of reverse inference. Reverse inference problems occur when researchers use brain activation results to infer cognitive processes. Since activity in any one brain area is associated with several processes, activation in a particular area is not incontrovertibly associated with a particular psychological process. This problem is partially mitigated when hypotheses center on well-defined areas of the brain that have been reliably correlated to specific cognitive processes (Huettel & Payne, 2009; Poldrack, 2006). The current investigation honed in on the DLPFC (one component of which is the rMFG), which has reliably been implicated in implementation of control, and the ACC, which has reliably been implicated in conflict identification (Kawashima et al., 1996; Kerns et al., 2004; MacDonald et al., 2000; van Veen & Carter, 2002). Hence in the current work, reverse inference might be partially mitigated by our focused hypotheses and the findings of the subsequent intervention study. Nonetheless, it is possible that diminished activity in the rMFG is caused by some other

Table 2
Voxels with statistically significant activation differences when making choices as a function of prior attention-demanding versus neutral condition.

Location	Hemisphere	Brodmann area	Talairach coordinates	Average *t*-Stat	Cluster size (voxels)
Middle frontal gyrus	*R*	9	39, 27, 35	−6.642	1180

Note: All x, y and z coordinates denote center of gravity for each cluster in Talairach coordinates.
Areas of statistically significant activation differences for the contrast of choices after attention-demanding versus neutral tasks ($n=16$, random effects ANOVA, $p<0.05$, Monte Carlo Estimation Minimum Cluster Size >324 mm^3, $\alpha<.05$).

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cognitive process that we have not considered and this is an important caveat to note.

Our intervention study also has shortcomings that could not be completely eliminated and should be acknowledged. The implementation and conflict interventions were designed to improve implementation and conflict monitoring, respectively. However, it is possible these interventions affected participants in ways that were not intended. For instance, like many experimental manipulations, it is possible our interventions generated demand effects. But demand effects are an unlikely explanation for our fMRI findings. This illustrates the value of using multiple methods to study one phenomenon.

Future research

Our studies suggest regulatory resource depletion affects people's ability to implement control without affecting conflict monitoring. But it is premature to accept the strong form of this argument—that depletion cannot impair conflict monitoring. In fact, there is some evidence supporting an alternative theory, that depletion affects conflict monitoring as well (Inzlicht & Gutsell, 2007). There are several differences between our studies that could explain these conflicting findings. First, Inzlicht and Gutsell (2007) measured depletion during performance of a Stroop task while we measured depletion during a preferential choice task. It is possible that the Stroop task and preferential choice task tax conflict monitoring and conflict identification resources differently. Second, Inzlicht and Gutsell (2007) limited their investigation to error-related negativity, which is a pattern of brain activity that likely originates in the ACC (van Veen & Carter, 2002). This means their study was sensitive to changes in the ACC but not to changes in the DLPFC. In contrast, our fMRI analysis was sensitive to activity in all parts of the brain. Given these earlier findings, it is safer to offer the more tentative assertion that depletion may independently affect either conflict identification or implementation of control. Future research to determine when one process or the other is depleted would be a notable accompaniment to the current work.

It is also possible that some implementation behaviors involve cognitive control while others involve motor control. Indirect evidence for this speculation is provided by a number of studies that find anatomical and functional connections between areas associated with self-control and the motor cortex (see Paus, 2001 for a review). More direct support comes from research by Brass and Haggard (2007) who have found that the DFMC is involved in cancelling motor responses. Cancelling motor responses could be an alternative way to exert self-control. Future studies could examine the possibility that motor control can be depleted by prior exertion of control.

Finally, our two stage model of self-control led us to theorize that participants must identify conflict and implement control in the first task to be depleted in the second task. But this might not be the case. It is possible that conflict identification or implementation of control alone could cause depletion. It is also possible that some depletion effects are aided by other factors such as narrowed attention (Muraven & Baumeister, 2000) or reduced motivation (Wan & Sternthal, 2008). We cannot investigate these possibilities with our data, but future behavioral studies could independently manipulate these factors to see how they affect depletion.

Conclusion

The current work presents a neural account of self-regulatory resource depletion, an influential model for explaining temporary failures of self-control. It appears that prior acts of self-control affect processing in the rMFG, an area of the brain that has been associated with the implementation of control. Further, it appears that implementation interventions can help mitigate the effects of regulatory resource depletion. The current work provides a theoretical and neuroscientific account of the mechanisms underlying the limited resource model. In doing so, we anticipate and hope that it will stimulate further work among scientists, practitioners, and policy makers who are interested in understanding why people temporarily lose self-control.

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Appendix. Behavioral pretests

Behavioral pretest 1

The first behavioral pretest was designed to verify that our self-control manipulation had the predicted impact on several measures of self-control failure. We measured participants' performance on the Stroop task[4] (Gailliot et al., 2007; Inzlicht & Gutsell, 2007; Richeson & Shelton, 2003) as well as their preferences for different types of snacks (indulgent versus healthy) (Hofmann, Rauch, & Gawronski, 2007; Ramanathan & Menon, 2006; Shiv & Fedorikhin, 1999; Vohs & Heatherton, 2000) following their exposure to the self-regulatory resource depletion manipulation. We predicted and found depleted participants preferred indulgent snacks and performed worse on the Stroop task relative to participants who had not been depleted of their self-regulation resources.

[4] In our case, participants saw stimuli that were presented in one of four colors (red, green, blue, and black). The stimuli were 1) words that were congruent with the font color (e.g., "red" in red font), 2) words that were incongruent with the font color (e.g., "red" in blue font), or 3) solid rectangles of the four colors. We refer to these conditions as congruent, incongruent, and neutral respectively. Participants were asked to identify the semantic content of the stimulus (i.e., the right answer to "blue" regardless of its color, is blue).

Procedures

Participants (n=60 undergraduate students, 20 male)[5] were assigned to one of two conditions: the attention demanding condition (which was expected to deplete self-regulatory resources) and the neutral condition. Stimuli were presented on desktop computers and responses were recorded electronically. Participants were exposed to four blocks of tasks. Initially, they performed a Stroop task. Second, they were exposed to the manipulation (attention demanding or neutral). Third, they performed another Stroop task. And fourth, they responded to several dependent measures of preferences, demographics and the like. Key dependent variables included reaction time and percent of correct responses on the Stroop tasks as well as preferences for indulgent versus healthy snacks and a manipulation check item regarding the degree of difficulty associated with the task ("How mentally demanding was the task?"; 1="very easy", 7="very hard").

Results

Participants in the attention demanding condition rated the task as more difficult (M=3.84, SD=1.95) than participants in the neutral condition (M=2.86, SD=1.46; $F(1,58)=4.8$, p=.0325). Further, participants in the attention demanding condition had a stronger preference for an indulgent snack (M=3.72; SD=2.16) than participants in the neutral condition (M=4.89, SD=2.23; $F(1,58)=4.28$, p=.043, where 1=preference for a Candy Bar and 7=preference for a Granola Bar) indicating that resource depleted participants preferred indulgent over healthy snacks.

In analyzing the Stroop task results, the percent correct in the first Stroop task was subtracted from the percent correct in the second Stroop task for each individual respondent (thus controlling for within participant variability). Participants who had been assigned to the attention demanding condition (and presumably were resource depleted) performed worse during the second Stroop task than they had in the first Stroop task (M=1.2% decline, SD=7.17), while participants who had been assigned to the neutral condition (and were therefore not resource depleted) improved Stroop performance during the second task (M=1.79% improvement, SD=4.49; $F(1,58)=3.60$, one-tailed p=.031). This result was particularly stark in the incongruent conditions; participants whose resources had been depleted performed equally poorly in both Stroop tasks (M=0.0% improvement, SD=13.44), while participants whose resources had not been depleted displayed improved performance during the second task (M=6.70% improvement, SD=9.06; $F(1,58)=4.08$, p=.048). In general, we conclude that resource depleted participants made relatively more mistakes on the second Stroop task (which followed the attention manipulation) than participants whose resources had not been depleted.

The Stroop task also allowed us to measure response latency. Measures of response latency observed in the first Stroop task were subtracted from values observed in the second Stroop task for each individual to obtain a difference measure which was log transformed. While both groups were quicker in performing the second Stroop task relative to the first, as expected, participants whose resources had been depleted sped up more (M=228 ms. faster, SD=181) than participants whose resources had not been depleted (143 ms. faster, SD=90, $F(1,58)=5.17$, $p=0.0267$). That is, resource depleted participants made quicker decisions relative to participants whose resources had not been depleted.

This pretest established that our manipulation of resource depletion was effective. Participants assigned to the attention demanding condition rated their task as more difficult than did participants assigned to the neutral condition. Further, participants in the attention demanding condition exhibited preferences (for candy bars over granola bars) and behaviors (errors on conflict laden incongruent stimuli as well as quicker responses, on the Stroop task) that reflected a reduction in self-control. These results indicate that our self-control manipulation had the expected effect on subsequent self-control tasks.

Behavioral pretest 2

We conducted a second pretest to ensure that our self-control manipulation would yield differences in self-regulation when participants were exposed to the repeated choice stimuli employed in our fMRI study. Participants (n=42) were assigned to the previously described attention demanding and neutral conditions and were subsequently exposed to the choice sets described in our fMRI study. Consistent with expectations, participants who had been assigned to the attention demanding condition made quicker decisions in the subsequent choice task compared with participants who had been assigned to the neutral condition ($M_{\text{attention}}$=8369 ms, SD=4333 ms$<M_{\text{neutral}}$=9466 ms, SD=6303; $F(1,1006)=10.38$, p=.001). This provides further evidence that our manipulation reduced self-control on a subsequent task.

[5] Participants (n=11) who were unable to accurately respond to a query on what study instructions had been provided (e.g., "not sure", "I can't remember") or provided Stroop responses that were woefully incorrect (n=5) (2 standard deviations away from the mean, a correct response rate of 9%, when they could have achieved a correct response rate of 25% by chance alone) were eliminated from further analysis.

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