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Self-Control Relies on Glucose as a Limited Energy Source: Willpower Is More Than a Metaphor

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The present work suggests that self-control relies on glucose as a limited energy source. Laboratory tests of self-control (i.e., the Stroop task, thought suppression, emotion regulation, attention control) and of social behaviors (i.e., helping behavior, coping with thoughts of death, stifling prejudice during an interracial interaction) showed that (a) acts of self-control reduced blood glucose levels, (b) low levels of blood glucose after an initial self-control task predicted poor performance on a subsequent self-control task, and (c) initial acts of self-control impaired performance on subsequent self-control tasks, but consuming a glucose drink eliminated these impairments. Self-control requires a certain amount of glucose to operate unimpaired. A single act of self-control causes glucose to drop below optimal levels, thereby impairing subsequent attempts at self-control.

Keywords: self-regulation, glucose, attention, emotion regulation, prejudice

Self-control (or self-regulation) is the ability to control or override one's thoughts, emotions, urges, and behavior. Self-control allows for the flexibility necessary for successful goal attainment, and it greatly facilitates adherence to morals, laws, social norms, and other rules and regulations. As such, it is one of the most important and beneficial processes in the human personality structure. A burgeoning body of evidence has linked good self-control to a broad range of desirable outcomes, including healthier interpersonal relationships, greater popularity, better mental health, more effective coping skills, reduced aggression, and superior academic performance, as well as less susceptibility to drug and alcohol abuse, criminality, and eating disorders (DeWall, Baumeister, Stillman, & Gailliot, in press; Duckworth & Seligman, 2005; Finkel & Campbell, 2001; Gailliot, Schmeichel, & Baumeister, 2006; Gottfredson & Hirschi, 1990; Kahan, Polivy, & Herman, 2003; Pratt & Cullen, 2000; Shoda, Mischel, & Peake, 1990; Tangney, Baumeister, & Boone, 2004; Vohs & Heatherton, 2000).

Self-control seems to rely on a limited energy or strength, such that engaging in a single act of self-control impairs subsequent attempts at self-control, as if some sort of energy had been used up during the initial act (for reviews, see Baumeister, Gailliot, DeWall, & Oaten, in press; Muraven & Baumeister, 2000). Although viewing self-control as an energy resource has served as a highly convenient metaphor that explains a broad range of empirical findings, the precise nature of the energy source of self-control has remained unspecified. In the present, we examined whether self-control does indeed rely on an actual energy source, namely, blood glucose.

Since Freud (1923/1961a, 1933/1961b), psychological theorizing about personality or the self has used energy models relatively sparingly. Yet, the human body is undeniably an energy system, and its very life depends on ingesting energy and then using it to fuel its activities, including complex psychological processes. The human brain consumes 20% of the body's calories even though it constitutes only 2% of the body's mass (Dunbar, 1998). In order for evolution to have selected in favor of such expensive psychological processes, those processes must have paid great adaptive dividends to offset such a high cost in calories. The capacity for self-control provides numerous benefits (e.g., Baumeister, 2005), and so it is plausible that self-control may have been one psychological process that was immensely valuable despite being so expensive in terms of caloric energy (glucose).

An accumulating amount of evidence is consistent with the notion that self-control relies on some kind of energy. For instance, after resisting the temptation to eat freshly baked cookies, participants in one study quit sooner on a subsequent task requiring effortful persistence, compared with participants who did not have to resist eating the cookies (Baumeister, Bratslavsky, Muraven, & Tice, 1998). Resisting the temptation to eat the cookies presumably depleted an energy resource that could otherwise have been used to persist on the subsequent task. A variety of other behaviors have been found to rely on and deplete this energy source as well, including managing one's impression (Vohs, Baumeister, & Ciarocco, 2005), suppressing stereotypes and prejudice (Gordijn, Hindriks, Koomen, Dijksterhuis, & Van Knippenberg, 2004; Richeson & Shelton, 2003; Richeson & Trawalter, 2005; Richeson, Trawalter, & Shelton, 2005), coping with thoughts and fears of dying (Gailliot et al., 2006), controlling one's monetary spending (Vohs & Faber, 2004), restraining aggression (DeWall et al., in

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press; Stucke & Baumeister, 2006), and managing one's intake of food and alcohol (Kahan et al., 2003; Muraven, Collins, & Nienhaus, 2002; Muraven, Collins, Shiffman, & Paty, 2005; Vohs & Heatherton, 2000).

Thus, there is ample evidence that self-control processes operate as if they depend on some kind of limited energy resource. But what might that energy resource actually be? Glucose may be one facet of the energy dynamics of self-control.

Self-Control and Glucose

Glucose is one vital fuel for the brain. The brain's activities rely heavily on glucose for energy (e.g., Laughlin, 2004; Siesjo, 1978; Weiss, 1986). The metabolization of glucose from the bloodstream allows each brain region to carry out its given functions (e.g., McNay, McCarty, & Gold, 2001; Reivich & Alavi, 1983).

Even though nearly all of the brain's activities consume some glucose, most cognitive processes are relatively unaffected by subtle or minor fluctuations in glucose levels within the normal or healthy range. Controlled, effortful processes that rely on executive function, however, are unlike most other cognitive processes in that they seem highly susceptible to normal fluctuations in glucose. For instance, low glucose has been linked with impaired performance on difficult (incongruent) but not easy (congruent) trials of the Stroop color word interference task (Benton, Owens, & Parker, 1994) and on complex but not simple reaction time tasks (Owens & Benton, 1994). One study found that low glucose was associated with poor performance on a driving simulation task, but only toward the end of the task, when participants were fatigued and the task was most demanding (as cited in Benton, 1990). Low glucose, therefore, seems to impair controlled or effortful processes but not the simpler or automatic processes, most likely because controlled processes require more glucose than automatic processes (Fairclough & Houston, 2004).

Self-control relies on controlled or executive processes in that the self must effortfully override urges, thoughts, emotions, and habitual or automatic response tendencies. Self-control, therefore, may be highly susceptible to fluctuations in glucose. Indeed, indirect evidence suggests that self-control failure may be more likely when glucose is low or when glucose is not transported effectively from the body to the brain. For instance, poor self-control is one of the leading causes of criminal behavior (Gottfredson & Hirschi, 1990; Pratt & Cullen, 2000), and several studies have linked criminal behavior to decrements in the processing of glucose (e.g., Bolton, 1979; Virkkunen & Huttunen, 1982). Problems with glucose have been associated with increases in aggression and impulsivity (Donohoe & Benton, 1999; Lustman, Frank, & McGill, 1991) and with decrements in concentration and emotion regulation (Benton & Owens, 1993; Benton et al., 1994). Alcohol impairs many forms of self-control (Baumeister, Heatherton, & Tice, 1994), and likewise, alcohol reduces levels of glucose in the brain and body (Altura, Altura, Zhang, & Zakhari, 1996). Failures at self-control are more likely later in the evening than during the day (Baumeister et al., 1994), and glucose is used less effectively later in the evening than during the day (Van Cauter, Polonsky, & Scheen, 1997). Glucose has also been found to facilitate coping with stress (Simpson, Cox, & Rothschild, 1974) and quitting smoking (West, 2001). These links between self-control and glucose suggest that glucose may be an important component of the energy source on which self-control relies.

Overview and Hypotheses of the Present Work

We used nine studies to test the hypothesis that decrements in self-control are caused in part by low glucose. This relatively large number of studies allowed us to provide converging multimethod evidence that would demonstrate the effects of glucose on a broad range of self-control behaviors and rule out potential alternative explanations. We hypothesized that completing a self-control task would use up a relatively large amount of glucose, compared with completing a cognitive task that does not require self-control. Because there exists an equilibrium between glucose in the bloodstream and the brain (Lund-Anderson, 1979), low blood glucose levels after an initial self-control task were then predicted to impair performance on subsequent self-control tasks, insofar as available quantities of glucose are too low for self-control to function unimpaired, and possibly because the self starts to avoid effortful activities in order to conserve its reduced remaining stock of glucose (Muraven, Shmueli, & Burkley, 2006). Restoring glucose to higher and optimal levels should replenish the ability to exert self-control.

The first step in the present investigation was to show that acts of self-control reduce the level of glucose in the bloodstream. In Studies 1 and 2, we examined whether completing a task that required self-control, as compared with a task that did not require self-control, would cause a drop in levels of glucose in the blood. Next, we sought to link reduced glucose to the behavioral signs of prior self-control exertion. In Studies 3–6, we tested the hypothesis that low glucose after an initial self-control task would be associated with greater self-control impairments, in the form of poorer performance on a subsequent self-control task. Having established that glucose correlated with greater impairments to self-control, we then turned to showing a causal role for glucose. More precisely, we aimed to show that experimental manipulations of glucose levels (administration of glucose drinks) would counteract the effects of prior exertions of self-control (see Studies 7–9). We predicted that participants who performed the initial self-control task would exhibit the typical pattern of performing worse than others on the second task but that receiving a glucose drink would reduce this effect.

Two of the major goals of this investigation were (a) to establish that blood glucose levels are reduced from before to after performing an initial self-control task and (b) to show that low levels of glucose after a first self-control task predict behavioral deficits on a second self-control task. In theory, we may have been able to do both of these in the same study. In practice, methodological complications rendered the two goals somewhat incompatible. Fasting facilitates (a) but interferes with (b). If participants have eaten recently, then some glucose may be entering the bloodstream at unpredictable intervals (possibly even when we might be assessing their glucose levels after the first self-control task), so the level may be rising when our hypothesis would predict a decrease, even if our hypothesis were completely correct. Hence, in Studies 1 and 2, we had participants fast prior to the experiment so their blood glucose would be stable apart from the impact of our manipulations. However, there is some evidence that hungry participants already perform poorly on self-control tasks,[1] which made it much harder to find behavioral effects of a laboratory manipulation of self-control depletion. Therefore, we did not require fasting in Studies 3–6 in order to obtain better behavioral data.

Study 1

Study 1 provided an initial test of the hypothesis that exerting self-control uses up a relatively large amount of glucose. Participants completed a task that either did or did not require self-control. At the end of this task, we assessed glucose levels. We predicted that the self-control task would diminish glucose relative to the task that did not require self-control.

Method

Participants. Participants were 110 undergraduates (69 women and 1 unreported) enrolled in an introductory psychology course. Seven participants indicated having medical conditions related to glucose (e.g., diabetes), and so their data were discarded from all analyses. This left a final sample of 103 participants (64 women and 1 unreported). Participants in this and all subsequent studies received credit toward fulfilling a course requirement.

Participants were instructed not to eat for 3 hr prior to arriving at the experiment. Glucose levels fluctuate regularly throughout the day as a result of eating (and for rather long and variable intervals after eating). Requiring participants to refrain from eating thus allowed glucose levels to stabilize, which greatly reduced extraneous variance in glucose measurement.

Procedure. Participants were run individually and were told the study was investigating physiological measures and task performance. First, the experimenter assessed baseline blood glucose levels. Blood samples were taken with single-use blood sampling lancets. Blood glucose levels were measured (mg/dL) using an Accu-Chek compact meter.

Next, participants completed the video task that served as the manipulation of self-control exertion. Participants watched a 6-min video (without sound) of a woman talking (modified from Gilbert, Krull, & Pelham, 1988). In the bottom corner of the screen, common one-syllable words (e.g., *hair*, *hat*, *pulse*) appeared individually for 10 s. Participants randomly assigned to the attention control condition were instructed to focus their attention only on the woman's face and to refrain from looking at the words. If they happened to look at the words, then they were to refocus their attention on the woman as quickly as possible. Participants randomly assigned to the watch normally condition were instructed to watch the video as they would normally. After completing this task, the experimenter assessed blood glucose levels a second time.

In Studies 1–8, we assessed current mood valence and arousal after participants completed the initial self-control task or prior to any subsequent self-control task. Participants completed either the Brief Mood Introspection Scale (Mayer & Gaschke, 1988), the Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988), or the UWIST Mood Adjective Checklist (Matthews, Jones, & Chamberlain, 1990). None of the mood measures (including the Valence and Arousal subscales) had a significant effect on the dependent measure in any study. To save space, we do not report all these null findings individually. In each study, participants were thanked and debriefed at the end of the experiment.

Results and Discussion

Analyses confirmed that the self-control task used up a relatively large amount of glucose. A 2 × 2 mixed model analysis of variance (ANOVA) indicated a significant interaction between attention control condition and time of measurement, $F(1, 100) = 6.08$, $p < .05$. Among participants in the attention control condition, glucose was lower after the video task ($M = 101.22$, $SD = 18.34$) than before ($M = 107.10$, $SD = 21.02$), $t(50) = -2.57$, $p < .05$. Among participants in the watch normally condition, glucose levels did not differ from before ($M = 102.24$, $SD = 21.20$) to after ($M = 103.24$, $SD = 18.71$) the video task ($t < 1$). Thus, all participants watched the same video, but glucose levels dropped only among participants who had to exert self-control while watching.

These results are consistent with the notion that exerting self-control uses up a relatively large amount of glucose. Blood glucose levels were lower after participants regulated their attention while watching a video—lower than their own levels before the video and lower than those of participants who had just watched the same video without controlling attention.

Study 2

The purpose of Study 2 was to provide additional evidence that self-control uses enough glucose to partially deplete the supply in the bloodstream. Suppressing stereotypes or prejudice, such as during the course of an interracial interaction, has been shown to deplete self-control strength (Gordijn et al., 2004; Richeson & Shelton, 2003; Richeson & Trawalter, 2005; Richeson et al., 2005; see also Richeson et al., 2003). Therefore, we examined in Study 2 whether an interracial interaction would deplete glucose.

Restraining prejudice may be more difficult for some people than for others. Therefore, Study 2 measured individual differences in internal motivation to respond without prejudice (Plant &

[1] In support of the notion that hunger obscures the effects of self-control exertion on subsequent behavior, a pilot study found that hunger impaired future self-control to the same extent as did prior self-control exertion. Specifically, participants ($N = 27$) were instructed to arrive hungry to the laboratory and completed the same video task used in Study 1. They were randomly assigned to one of three conditions: hunger/attention control, hunger/watch normally, or no hunger/watch normally. Participants in the no-hunger/watch normally condition received an orange juice drink and a muffin bar to eat after the video task. Participants in the other two conditions proceeded immediately to the next part of the experiment.

Next, participants completed the Stroop task for 3 min. The number of trials completed (i.e., speed) on this task served as the dependent measure of Stroop performance.

A one-way ANOVA indicated a main effect of condition, $F(1, 24) = 4.22$, $p < .05$. Participants in the no-hunger/watch normally condition ($M = 198.88$, $SD = 8.72$) completed more Stroop trials than participants in the hunger/watch normally ($M = 168.60$, $SD = 7.80$) and no-hunger/attention control ($M = 168.78$, $SD = 8.22$) conditions. The difference between the hunger/watch normally and no-hunger/attention control conditions was not significant ($t < 1$). Thus, the Stroop measure suggested that self-regulatory performance was impaired to about the same degree by prior self-regulation as by hunger. These results are also consistent with the hypothesis that poor self-control is caused by low glucose, insofar as hunger is associated with low glucose (e.g., Cox, Eickhoff, Gonder-Frederick, & Clarke, 1993).

Devine, 1998), which were predicted to moderate the consumption of glucose during an interracial interaction. Internal motivation reflects the desire to respond without prejudice because of the personal importance of endorsing nonprejudiced beliefs. Internally motivated people are less likely than others to respond with racial bias across all sorts of situations. For them, suppressing prejudice should be a well practiced and hence presumably automatic way of acting, and therefore it should be easier for them to avoid expressing bias in our laboratory (Plant, 2004). In contrast, people who are low in internal motivation to avoid prejudice prefer to avoid interracial interactions than to struggle to suppress their views while in them (Plant, 2004), and so when they find themselves having to suppress prejudice in a sensitive situation, they may have to exert considerable self-control to speak and act appropriately. For them, unlike the others, stifling prejudicial thoughts may require effortful self-control rather than falling back on a habitual pattern. We therefore expected that an interracial interaction might reduce glucose primarily among participants low in internal motivation to respond without prejudice.

Method

Participants. The final sample included 38 White college undergraduates (29 women). We excluded from all analyses 1 participant because he was diabetic. Participants were randomly assigned to interact with either a Black or a White experimenter. Participants were instructed not to eat for 3 hr prior to arriving at the experiment.

Procedure. Upon arrival at the laboratory, participants were greeted by a Hispanic female experimenter. Participants were told that the study was examining factors related to different tasks and physiological measures.

First, we assessed initial glucose levels. Next, participants had a 5-min conversation with either a Black or a White female experimenter. After introducing themselves, participants were asked to state their opinions on affirmative action and criminal profiling (in counterbalanced order) and were given 2 min to discuss each topic. These topics were chosen because they involve unequal treatment of individuals on the basis of race and would therefore be likely to activate racial stereotypes.

Glucose levels then were assessed a second time. Last, participants completed a questionnaire on which they indicated the extent to which they felt like they exerted effort during the interaction so as to avoid saying anything negative, using a 9-point scale ranging from 1 (*very little*) to 9 (*a lot*). The questionnaire also contained the Internal Motivation to Respond Without Prejudice scale (IMS; Plant & Devine, 1998), which contains five items (e.g., "Because of my personal values, I believe that using stereotypes about Blacks is wrong").

Results and Discussion

Glucose levels after interaction. The hypothesis was that discussing racially sensitive material with a member of another race would require self-control and therefore deplete glucose—mainly for people who do not habitually stifle prejudicial thoughts and feelings (i.e., for people low in IMS). A regression analysis that regressed standardized IMS, condition (same-race vs. interracial interaction), and their interaction upon postinteraction glucose levels yielded the predicted significant interaction between IMS and experimental condition ($b = 4.41$), $t(1, 33) = 2.20$, $p < .05$ (see Figure 1). The postinteraction glucose levels were controlled for baseline (preinteraction) glucose levels, which did not differ by condition or IMS (ts < 1). To interpret the interaction, we assessed the simple effect of condition among participants who were relatively high versus low in IMS (one standard deviation above and below the mean on IMS, respectively; Aiken & West, 1991). Results indicated that the effect of condition was significant for low-IMS participants ($b = -3.28$), $t(1, 33) = -2.33$, $p < .05$, but not for high-IMS participants ($b = 1.16$), $t(1, 33) = 0.92$, $p = .36$. Thus, discussing a sensitive topic with a member of a different race used up a significant amount of glucose among people with low IMS. Glucose was not depleted in people who discussed the same topics with members of their own race or among people who are dispositionally motivated to stifle prejudicial thoughts and feelings. This pattern is consistent with the view that acts of self-control deplete blood glucose.

Effort. Interracial interactions require self-control because one often exerts effort to avoid expressing negative attitudes or opinions (Richeson & Trawalter, 2005). In support of this, in the interracial interaction condition, IMS scores predicted self-reported effort, $r(21) = -.48$, $p < .05$; effort predicted postinteraction glucose levels (controlling for preinteraction glucose levels) $r(18) = -.54$, $p < .05$; and a Sobel test for mediation pointed toward the conclusion that effort mediated the effect of IMS on postinteraction glucose levels, although it fell short of two-tailed significance ($z = 1.79$, $p = .07$). Glucose dropped primarily among low-IMS participants because they found the interracial interaction more effortful than did high-IMS participants. Effort did not appear to mediate the effect of IMS in the same-race condition ($z = -.20$, *ns*), and the preconditions for mediation were not met either. These findings suggest that the self-regulatory effort needed to avoid negative responses during an interracial interaction depletes an energy source on which self-control relies (i.e., glucose).

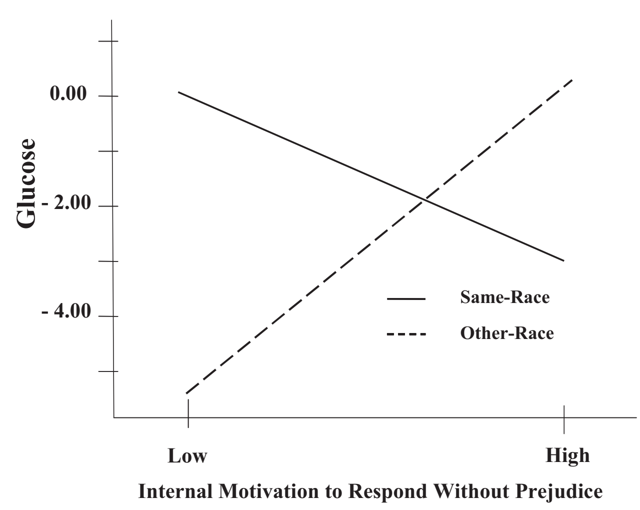

Figure 1. Glucose levels after an interaction (controlling for glucose levels before the interaction) as a function of interaction condition and internal motivation to respond without prejudice (see Study 2).

Study 3

With Study 3, we began testing the hypothesis that low levels of blood glucose following a self-control task would predict poor performance on behavioral measures of self-control. In Studies 3–6, all participants were subjected to an initial depleting task, and we assumed that these would be more depleting to some than to others. The prediction for Studies 3–6 was that the participants with the lowest levels of blood glucose would perform worst at self-control. After measuring blood glucose, we used the attention control task from Study 1 to create depletion. Following a second glucose measurement, participants completed the Stroop task, which is one of the most frequently used measures of self-control (e.g., Richeson & Shelton, 2003; von Hippel & Gonsalkorale, 2005). The Stroop task requires the participant to override an incipient response (i.e., to read aloud the name of the word) in order to say instead the color in which the word is printed, and in that sense it requires self-regulation. Lower blood glucose should impair Stroop performance in the sense of causing the person to take longer to get the right answer and in terms of making more errors along the way.

Method

Participants. Participants were 16 college undergraduates (12 women). We excluded from this sample 1 additional participant because of equipment malfunction.

Procedure. Participants were told that the study was examining the relationship between physiological factors and task performance. First, baseline blood glucose levels were assessed. Next, participants completed the attention control task used in Study 1. All participants were instructed to exert self-control by refraining from looking at the words in the video. At the end of the task, glucose levels were assessed a second time.

Last, participants completed the Stroop task. They were shown words (i.e., *red*, *green*, and *blue*) that appeared in a font color (i.e., red, green, or blue) that diverged from the meaning of the word (e.g., *red* appeared in blue ink). Participants completed 80 trials for which they were to state aloud the color ink that each word appeared in and to refrain from reading the word. The amount of time participants took to complete the Stroop task (i.e., speed) and the number of errors (i.e., accuracy) constituted the dependent measures of Stroop performance. The assumption behind that measure is that effective self-control enables the person to override the initial response to say the word so as to be able to state the color of the ink. When self-control is weak or ineffective, the person takes longer to override the initial (wrong) response, or the person makes more errors.

Results and Discussion

Glucose levels at the start of the experiment did not predict Stroop performance (i.e., neither time to complete the Stroop nor errors; $-.20 < rs \leq -.13$, $ps > .48$). In contrast, lower glucose after having watched the video was associated with poorer Stroop performance (i.e., taking more time to complete the Stroop task), $r(14) = -.62$, $p < .05$, and this relationship remained significant after controlling for baseline glucose levels, $r(12) = -.66$, $p < .05$. Errors on the Stroop task showed a similar though nonsignificant pattern, such that lower glucose was associated with making more errors, $r(14) = -.23$, *ns.*

These findings are consistent with the idea that self-control impairments stemming from a prior act of self-control are attributable to low glucose. Participants with less glucose after an initial self-control task performed worse at a subsequent self-control task.

One alternative explanation for these findings is that low glucose simply made participants slow to respond rather than impairing their self-control. In Studies 4–6, we addressed this limitation by using a dependent measure that was not directly related to speed of responding.

Studies 4–6

Studies 4–6 provided conceptual replications of Study 3. In each study, we had participants engage in a self-control task designed to impair their self-control afterwards. Participants either controlled their attention (see Study 4), completed the Stroop task (see Study 5), or regulated their emotions (see Study 6). Regarding the last of these, emotion regulation is a common, well-recognized form of self-control and likewise has been shown to impair later attempts at self-control (e.g., Muraven, Tice, & Baumeister, 1998). In each study, blood glucose was measured before and after the initial self-control task.

Last, participants were assigned to perform a figure-tracing task. Unbeknownst to participants, the task was unsolvable, and we timed how long they persisted. Persistence at the unsolvable task requires self-control because the discouraging, frustrating failures at the task give rise to impulses to quit, which the person must override in order to continue striving on the task (see Baumeister et al., 1998). We predicted that low glucose after the initial self-control task would be associated with less effortful persistence.

Method

Participants. Study 4 had a final sample of 12 participants (10 women). Two additional participants were excluded, 1 because a second glucose reading could not be obtained and the other because the participant erroneously claimed to have solved the figure-tracing task. Study 5 had a final sample of 23 participants (15 women). Four additional participants were excluded, 1 because a second glucose reading could not be obtained and 3 others who either suspected the figure-tracing task was unsolvable or erroneously claimed to have solved it. The final sample in Study 6 was 17 participants (7 women). Two additional participants were excluded from analyses. One of the excluded participants did not complete the emotion regulation task, and the other was an outlier (three standard deviations above the mean) on the dependent measure.

Procedure. Participants were told that the study was investigating the relationship between physiological factors and task performance. Participants first provided a blood sample to assess glucose level. Next, they either completed the same attention control task used in the previous studies (see Study 4), the Stroop task used in Study 3 for 4 min (see Study 5), or an emotion regulation task (see Study 6). For the emotion regulation task, participants watched a 2-min video clip of animals in a slaughterhouse and a 2-min video clip of the comedy show *Jay Leno*.

Participants in Study 6 were instructed to suppress any emotional feelings or reactions they had while watching the clips. After their respective task, participants provided a second sample of blood to assess glucose.

Last, all participants completed the figure-tracing task, adapted from Glass, Singer, and Friedman (1969) and Feather (1961). Participants were given a figure and asked to trace the lines of the figure without lifting their pen. Participants were told that they would be given five figures in total and were to solve each of them as quickly as possible. They were to notify the experimenter as soon as they solved each figure or decided that they could not and wanted to give up. The first figure given to participants, however, was unsolvable. Participants were surreptitiously timed. Participants were given a maximum of 20 min for the task, at which time any participants still working were asked to stop.

Results and Discussion

Glucose levels at the start of each experiment were not significantly related to persistence (all rs $< .27$, ps $> .24$). Low glucose after the initial self-control task, however, was associated with persisting less on the figure-tracing task in all three studies; Study 4 $r(10) = .56$, $p < .05$; Study 5 $r(21) = .45$, $p < .05$; Study 6 $r(15) = .43$, $p < .05$. (Because these studies were replications, we used one-tailed tests to examine our hypothesis.) Furthermore, the correlation between glucose levels after the initial task and persistence remained significant when controlling for glucose levels at the start of each experiment (ps $< .05$). The link between posttest glucose levels and persistence, therefore, did not appear attributable to initial glucose levels.

Although the samples in these three studies were small, the magnitude of the correlations was consistently quite robust. The consistency of findings across the three different samples and methods lends confidence to the conclusion that low levels of glucose are associated with decrements in self-control.

Moreover, these results help to refute the alternative explanation for Study 3 that low glucose simply makes people generally slower at tasks rather than impairing their self-control. If low glucose only made people slow at various tasks, then one might have expected that low glucose would have predicted greater persistence (i.e., being slower to give up).

Study 7

The results thus far support the hypothesis that impairments to self-control following an initial self-control task are linked to low glucose in the bloodstream. Studies 1 and 2 showed that exerting self-control reduced blood glucose levels. Studies 3–6 showed that lower glucose after an initial exertion of self-control predicted poorer self-control on the second task (e.g., quitting sooner on the frustrating puzzle). The remaining studies sought to provide evidence of a causal relationship between glucose and self-control by using direct manipulations of blood glucose, namely, drinking a glucose beverage. Glucose is absorbed into the bloodstream at a rate of 30 calories per minute and after about 10 min can be metabolized to the brain (Donohoe & Benton, 1999). Hence, glucose drinks are a viable means of increasing the amount of glucose available for self-regulatory tasks, provided that one allows some time for the glucose to reach the bloodstream. Participants in Study 7 first completed either a task that required self-control (attention control as in the previous studies) or a task that did not require self-control.

Participants then drank Kool-Aid lemonade that had been sweetened either with sugar (and hence glucose) or Splenda (a good-tasting sugar substitute that does not increase blood glucose). The sugar lemonade shake should restore glucose and therefore would be expected to replenish self-control strength after the initial self-control task.

Hence, we predicted that participants who controlled their attention during the video task would perform worse on a subsequent Stroop task than participants who did not control their attention, but that a glucose drink would attenuate this effect.

Method

Participants. Participants were 62 college undergraduates (49 women and 1 unreported). We excluded from this final sample 1 additional participant who chose not to consume the drink. Participants were randomly assigned to depletion and glucose conditions. They were randomly assigned among the conditions. The two variables (attention control and lemonade content) were manipulated orthogonally.

Procedure. Participants were told that the study was examining factors related to different tasks and food. Participants first completed 20 Stroop trials (as in Study 3) as a baseline measure of Stroop ability. They then were administered the attention control manipulation used in Study 1, with half simply watching the video and the other half being instructed to keep their attention focused on the woman and not on the words while watching it. Study 7 added a manipulation check. After watching the tape, participants rated how often they had looked at the woman and the words, respectively.

Next, participants were given 14 ounces of lemonade sweetened with either sugar (glucose condition) or a sugar substitute (placebo condition). The glucose drink contained approximately 140 calories, whereas the placebo contained 0 calories. Participants and the experimenter were blind to condition. Participants consumed the glucose drink and then completed three measures of liking for the drink (e.g., "How pleasant was it for you while drinking the beverage?"; $\alpha = .63$) that were embedded among other filler measures intended to bolster the cover story regarding the taste and appearance of the drink. Participants then completed filler questionnaires for 12 min to allow the glucose from the drink (if they had any) to be metabolized (Donohoe & Benton, 1999). Last, participants completed 80 Stroop trials separated into four blocks. Speed and errors on the Stroop task constituted the dependent measures of self-control performance.

Results and Discussion

Manipulation check. Participants appeared to be successful in following the video task instructions. Participants in the attention control condition reported having looked at the words ($M = 2.03$, $SD = 0.68$) less often and at the woman ($M = 6.72$, $SD = 0.45$) more often than participants in the watch normally condition reported having looked at the words ($M = 4.76$, $SD = 1.95$) and woman ($M = 5.12$, $SD = 1.44$), respectively (ts > 4.30, ps $<$ .001).

Stroop performance. A 2 (self-control condition) × 2 (glucose condition) between-subjects analysis of covariance (ANCOVA) on the number of errors made on the final Stroop task (controlling for errors at baseline) indicated that the main effects of self-control condition and glucose condition were not significant (Fs < 2.23, ps $> .14$). Their interaction, however, was significant, $F(1, 57) = 5.04$, $p < .05$, and consistent with predictions (see Figure 2 for adjusted means). In the placebo condition, attention control participants made more errors than watch normally participants, $F(1, 58) = 5.14$, $p < .05$, $d = 0.73$. This, however, was not the case in the glucose condition ($F = 1.12$, *ns*). A glucose drink thus eliminated the tendency for an initial self-control task to impair Stroop performance, consistent with the hypothesis that glucose replenishes what has been depleted.

A 2 (self-control condition) × 2 (glucose condition) ANOVA on speed on the Stroop indicated no significant effects (Fs < 1.76, ps $\geq .19$). To be sure, there was no speed–accuracy trade-off, such as if attention control participants in the placebo condition made more errors because they responded faster. The above interaction between self-control condition and glucose condition on the number of errors on the Stroop remained significant even when controlling for speed, $F(1, 56) = 6.18$, $p < .05$.

This pattern of results diverges from Study 3, in which speed on the Stroop rather than errors was more sensitive to glucose. This difference is probably attributable to the different methods used in Studies 3 and 8. In Study 3, participants completed 80 Stroop trials without a break, and so performing quickly (rather than making errors) was probably more onerous and hence more sensitive to glucose. In Study 7, the Stroop trials were divided into four blocks. The delay between blocks probably allowed participants to maintain their speed, and so avoiding errors was probably more onerous.

Liking for the drinks. The effects of depletion and glucose did not appear to be the result of liking for the drinks. In particular, the interaction between self-control condition and glucose condition on the number of errors on the Stroop approached significance when controlling for liking ($F = 3.47$, $p = .07$).

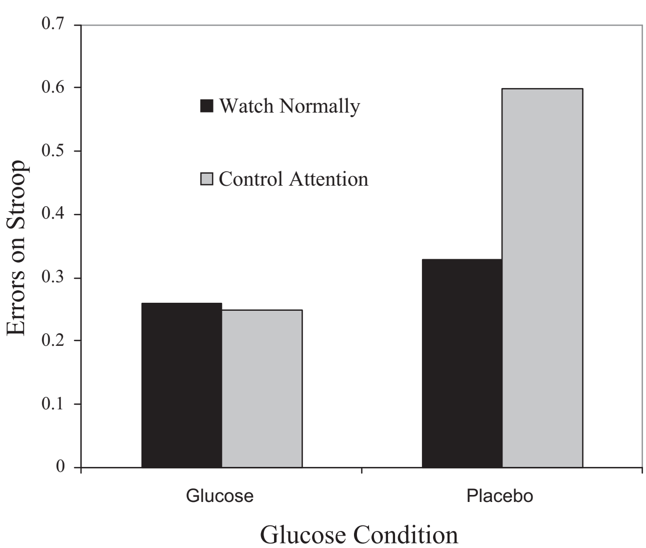

Figure 2. Stroop performance as a function of self-control and glucose conditions (see Study 7).

Study 8

Study 8 sought additional evidence that increasing glucose levels can counteract the detrimental effects of prior efforts at self-control. More precisely, in Study 8, we examined whether glucose would improve self-control among people who have coped with thoughts and fears of dying. The thought of death can be aversive and threatening, and people therefore seem motivated to avoid thinking about death (e.g., Aries, 1981; Becker, 1973). Past research has indicated that avoiding the thought of death is effortful and demanding (Arndt, Greenberg, Solomon, Pyszczynski, & Simon, 1997; Greenberg, Arndt, Schimel, Pyszczynski, & Solomon, 2001) and requires self-control (Gailliot et al., 2006). Likewise, thinking about death (i.e., mortality salience) has been found to impair subsequent performance on tasks that require self-control (e.g., the Stroop task), presumably because the self-control expended to cope with the thought of death depletes the energy source on which self-control relies (Gailliot et al., 2006). To assess whether glucose underlies self-control, we examined whether a glucose drink would benefit self-control after a mortality salience induction.

First, participants received either a glucose drink or a placebo. We administered it first on the assumption that the glucose would start to reach the bloodstream around the time participants completed the next task, at which point those who had coped with thoughts of death would otherwise be suffering from depleted glucose. They then wrote about either death or a control topic (dental pain). For the subsequent self-control task, participants were given a sheet filled with word fragments and were asked to solve them all. The word fragments were relatively easy, and with enough persistence (self-control), one could eventually solve each one by substituting into the word fragment different letters in the alphabet. Consistent with the idea that coping with thoughts of death impairs self-control afterwards, Gailliot et al. (2006) found that mortality salience caused participants to leave more word fragments unsolved, suggesting that mortality salience activated thoughts of death, and the person had to use his or her resources in order to defend against that threat, resulting in less resources available for making oneself persist on the word fragment task. The present experiment was designed to extend this finding by showing that a glucose drink attenuates this effect.

Method

Participants. Participants were 73 undergraduates (51 women). One additional participant was excluded from all analyses because this participant declined the drink. Participants were randomly assigned to mortality salience versus dental pain and glucose drink versus placebo conditions.

Procedure. Participants were told that the study was investigating food and personality. First, participants consumed either a glucose drink or a placebo and completed measures of taste and liking for the drink. The drinks and measures were the same as those used in Study 7.

Next, participants in the mortality salience condition were asked to describe the emotions that the thought of their own death aroused in them and to write about what would happen to their bodies as they physically die (see Rosenblatt, Greenberg, Solomon, Pyszczynski, & Lyon, 1989). Participants in the dental pain condition answered parallel questions about dental pain.

Participants next worked on a crossword puzzle and completed a filler questionnaire. These tasks took approximately 6 min. This delay was intended to allow participants to cope with any thoughts of death they might have had and hence consume the energy on which self-control relies (see Gailliot et al., 2006).

Participants then received a sheet that contained 20 word fragments (e.g., —WER) and were asked to solve all of them. The number of word fragments left unsolved constituted the dependent measure of self-control. The word fragments were relatively easy to solve, and with enough persistence (self-control), participants could have solved them all. Therefore, we used the number of unsolved fragments as the measure of poor self-control.

Last, participants completed the 33-item Marlowe-Crowne Social Desirability Scale (Crowne & Marlowe, 1960), which allowed us to assess whether any differences in the number of unsolved word fragments may have been attributable to response bias rather than to poor self-control. Participants then estimated the number of calories they thought that their drink had contained, as a check of whether there was any discernible difference in taste between the glucose and placebo drinks that may have influenced persistence at solving the word fragments.

Results and Discussion

Unsolved word fragments. We predicted that mortality salience would cause participants to leave more word fragments unsolved but that a glucose drink would eliminate this effect, and hence that mortality salience participants who consumed the placebo drink would leave more word fragments unsolved than any other group of participants. A 2 (mortality salience condition) × 2 (glucose condition) ANOVA on the number of unsolved word fragments produced no significant effects ($Fs < 2.02$, *ns*). To test our specific prediction, which constituted a theoretical replication of Study 7, we conducted a planned comparison, which confirmed our prediction, $F(1, 69) = 5.45$, $p < .05$ (see Figure 3).

In the placebo condition, mortality salience participants left unsolved more word fragments than did dental pain participants, $F(1, 69) = 3.91$, $p = .05$, $d = 0.33$. Thus, mortality salience impaired self-control. In the glucose drink condition, mortality salience participants did not differ from dental pain participants in the number of word fragments left unsolved ($F < 1$). A glucose drink thus eliminated the detrimental effects of mortality salience on self-control. These results suggest that the self-regulatory impairments following mortality salience may be at least partly attributable to low glucose.

Social desirability, calories, and ratings of liking. Analyses indicated that the obtained pattern of results was likely not attributable to differential liking for the drinks, social desirability, or estimations of the caloric content of the drinks. For instance, the number of word fragments left unsolved was not significantly related to any of these factors ($ps > .53$; $p = .21$ for social desirability), and the planned comparison reported above remained significant or approached significance when controlling for each of these factors ($ps \leq .06$). Moreover, estimations of the caloric content of the drinks did not differ between those who consumed the glucose drink and those who consumed the placebo ($F < 1$).

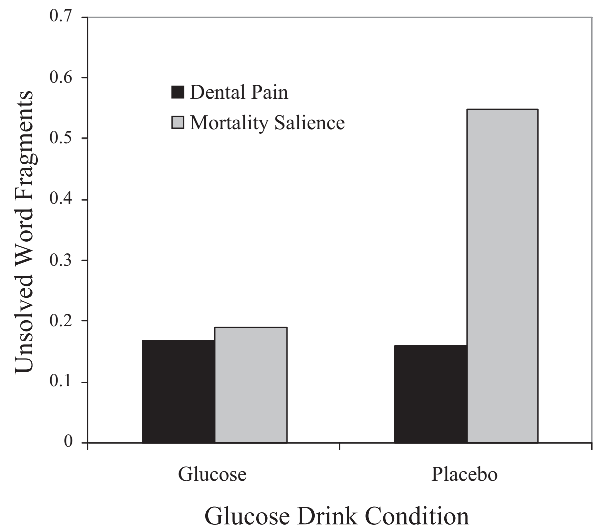

Figure 3. Effortful persistence as a function of mortality salience and glucose conditions (see Study 8).

Study 9

In the final study in this investigation, we sought to apply the link between glucose and self-control to an important form of interpersonal behavior, namely, helping. Helping is oftentimes effortful (see, e.g., Dawkins, 1976) and hence requires some amount of self-control. Indeed, previous studies show that an initial act of self-control reduces helpfulness later on (Gailliot, Maner, DeWall, & Baumeister, 2005) as well as other forms of prosocial behavior (Finkel & Campbell, 2001; Vohs, 2004).

Study 9 was a field experiment. We had participants exert self-control by taking an actual examination in their psychology course. Previous work has confirmed that taking exams or engaging in logical reasoning both require self-control (Gailliot et al., 2006; Schmeichel, Vohs, & Baumeister, 2003), and other work has shown that taking a difficult exam reduces glucose (Hall & Brown, 1979). Study 9 did not have a no-self-control (control) condition, insofar as everyone took the exam, but we were able to assess individual differences in the extent of self-control exertion. Specifically, the experimenter recorded the sequential order in which participants finished the exam. Gailliot et al. (2005) found that taking longer to complete an exam was associated with higher scores on a questionnaire measure of impaired self-control (see Twenge, Muraven, & Tice, 2004).

After finishing the exam, participants were randomly assigned to receive a glass of lemonade that was either high or low in glucose. Then their willingness to help others was measured with two items: one involved donating money to charity, and the other involved helping a fellow student with a housing problem. If glucose underlies self-control and self-control facilitates helping, then participants who consume the glucose rather than the placebo drink should be more willing to help.

Method

Participants. Participants were 18 undergraduates (10 men). We excluded from all analyses 1 additional participant who was an outlier (nearly three standard deviations above the grand mean) on the dependent measure. Participants were randomly assigned to a glucose or placebo drink condition.

Procedure. Participants were told the study was investigating the relationship between their attitudes and factors related to food. First, participants completed a 26-item multiple-choice exam that was an actual examination that counted toward the course grade. The experimenter recorded the order in which participants finished (e.g., first, second, third), as a measure of the duration of self-control exertion.

The actual experiment began after participants finished their exam. First, when participants turned in their exam, they were handed either a glucose or placebo drink. Participants and the experimenter were blind to condition. They then completed measures of liking for the drink ($\alpha = .63$) that were embedded among other filler measures regarding the taste and appearance of the drink intended to bolster the cover story. Participants then sat quietly for approximately 14 min to allow the glucose to be metabolized. (The reason for the delay was not explained to participants.)

Last, participants responded to two hypothetical scenarios that assessed their willingness to help strangers. For the first scenario, participants were to indicate how much money they would donate to a charity. For the second scenario, participants were told to imagine that a stranger from their class had been evicted from his or her apartment. Participants were to indicate, on a 7-point scale, what they would do to help him or her, with higher points on the scale representing more labor-intensive forms of helping. Specifically, participants' options were to: (1) do nothing, (2) give him or her an apartment guide, (3) help him or her find a new place to live by driving him or her around for a few hours, (4) offer to have him or her come to stay with the participant for a couple of days (provided the participant had space), (5) offer to have him or her come stay with the participant for a week (provided the participant had space), (6) offer to have him or her come stay with the participant until he or she found a new place (provided the participant had space), or (7) offer to have him or her come live with the participant rent free (provided the participant had space). Responses to the two scenarios correlated moderately strong, $r(16) = .63$, $p < .05$, and so they were standardized and averaged to form the final dependent measure of helping that ranged from $-.90$ to 2.46.

Results and Discussion

Likelihood of helping. Participants in the glucose condition ($M = 0.48$, $SD = 0.95$) indicated that they were willing to give significantly more help than those in the placebo condition ($M = -0.61$, $SD = 0.27$), $t(16) = 3.13$, $p < .01$, $d = 1.57$. Thus, after exerting self-control, consuming a glucose drink increased the likelihood and extent of helping.

Exam effort and likelihood of helping. We used the order in which participants completed the exam as a rough index of self-regulatory effort expended on the exam. Exam completion order does not appear to be related to intelligence or exam performance (e.g., Bridges, 1985), and it therefore seemed reasonable that taking longer on the exam reflected a greater expenditure of effort. In other words, independent of ability, the students who spent longer on the exam would have exerted effort for a longer period of time and therefore were likely to have used more self-control than the others.

Among those participants who received no glucose, likelihood of helping correlated negatively and quite strongly with exam completion order, $r(6) = -.83$, $p = .01$. Those who took longer on the exam offered less help. This fits the hypothesis that working long and hard on the exam depletes some resource that could otherwise be used to increase helpfulness. In the glucose condition, however, the relationship between helping and completion order was not significant, $r(8) = .29$, *ns*, and if anything, the relationship was in the opposite direction. Moreover, the strength of this relationship was significantly different than in the placebo condition ($z = 2.52$, $p < .05$). To the extent that taking longer on the exam reflected expending more self-control effort, then it appears that glucose eliminated the effect of self-control exertion (taking an exam) on helping.

Ratings of liking. Ratings of liking for the drinks did not differ between the glucose and placebo conditions ($t < 1$). Furthermore, these ratings were not significantly related to helping ($r < .22$, *ns*). It therefore does not appear that the difference in helping between the two conditions was attributable to liking for the drinks. The most parsimonious conclusion seems to be that glucose increased helping by counteracting the effects of prior self-control exertion. Because of the small sample size, however, we do present these results with some caution.

General Discussion

Self-control is one of the most important and central processes in personality and self-theory. Past work has shown that self-control operates as if a limited resource is consumed or expended in the process. The nature of such a resource, however, has remained a matter of conjecture and metaphor. The goal of this investigation was to flesh out that model by moving from metaphor to at least one plausible physiological process. Specifically, we investigated the hypothesis that some patterns of poor self-control are attributable to drops in glucose.

Three main sets of findings supported the hypothesis that self-control depends on glucose. First, measurements of blood glucose showed significant drops following acts of self-control (e.g., during an interracial interaction), primarily among participants who worked hardest. Second, low glucose after an initial self-control task (e.g., emotion regulation) was linked to poor self-control on a subsequent task. Third, experimental manipulations of glucose reduced or eliminated self-control decrements stemming from an initial self-control task.

By testing hypotheses using a variety of methods, the present findings sought to rule out a variety of alternate explanations. The improvements and impairments of self-control were not linked to mood, arousal, or other emotional states. Neither the taste nor the pleasure of the glucose snacks appeared to be a factor. The effects were not limited to any particular sort of task or measure. In fact, the procedures of these nine studies were deliberately set up to encompass a variety of behaviors, including well-validated and artificial laboratory measures (e.g., the Stroop task) and complex social behaviors (e.g., willingness to help a stranger).

Implications, Qualifications, and Future Directions

The present results suggest that self-control involves blood glucose and that the effects of an initial self-control task stem partly from reduced levels of glucose. As our title indicates, willpower is more than a metaphor. The nature of the resource that gets depleted has been a puzzle since the earliest findings on self-control depletion emerged (Baumeister et al., 1998). Some researchers have thought that self-control depletion was primarily a motivational deficit. This view may have been (somewhat unwittingly) encouraged by Muraven and Slessareva's (2003) demonstration that offering motivational incentives could counteract depletion effects. However, the present results suggest that self-control depletion involves a shortage of fuel for brain activities. As Muraven and Slessareva showed, behavior during that state can still respond to motivational incentives, but the state of self-control depletion is not primarily a deficit in motivation. By analogy, money may induce a person to continue working despite physical exhaustion, but that does not mean that physical exhaustion is essentially the result of a lack of money. Insofar as self-control depletion is a deficit in fuel, it reflects an impairment in capacity to perform not in desire (motivation) to perform, even though stimulating desire can sometimes offset a reduced capacity.

Another implication of the present work is that individual differences in glucose processing may contribute to different outcomes in self-control. Consistent with that suggestion, juvenile delinquents lack self-control (Gottfredson & Hirschi, 1990; Pratt & Cullen, 2000), and there is some evidence that juvenile delinquents process and tolerate glucose less effectively than comparable adolescents who do not have legal troubles (Gans et al., 1990; Matykiewicz, La Grange, Vance, Mu, & Reyes, 1997).

There is no reason to assume, however, that self-control is unique in its reliance on blood glucose. As far as we understand, all brain processes use some glucose, though some use more than others and are therefore more susceptible to fluctuations of the supply in the bloodstream. We would certainly expect that the patterns we have observed for self-control would generalize to other executive functioning or controlled processing. Evidence is accumulating that these other executive processes rely on the same energy source as self-control. Engaging in effortful choice and decision making has been shown to lead to impairments in subsequent self-control (Baumeister et al., 1998; Vohs, Baumeister, Twenge, Schmeichel, Tice, & Crocker, 2004). Along the same lines, controlled thinking processes, such as logical reasoning and extrapolation, are impaired among people who have performed recent acts of self-control (Schmeichel et al., 2003). We regard the self as the controller of controlled processes, and so its effortful activities are likely to involve glucose dynamics just like self-control. It is also plausible that there are some additional brain activities that would not involve the self but would still depend on the glucose in the same way, though we do not know just what those might be. For now, the most reasonable and parsimonious formulation would seem to be that the agentic, effortful activities of the self use significant amounts of glucose and are impaired when the supply of glucose has been depleted.

Still, it seems likely that relatively few psychological processes are as expensive as self-control in terms of requiring large amounts of glucose. There are two reasons for thinking that self-control is unusual, even if not unique. First, what it accomplishes is rather advanced and difficult. We assume that the psychological system evolved to want and do things. To interrupt and override these well-established responses, especially after they are already in process, seems quite difficult. In plain terms, an animal may have evolved to feel and act on strong desires, such as for food or sex, and so self-control requires an inner mechanism strong enough to counter those powerful responses. Second, the widespread occurrence of self-control failures is evidence that self-control is not easy, and high metabolic cost would be one likely explanation for this.

Not all self-control processes will be equally expensive, either. The present results showed ample evidence of individual differences. Studies 2–6 specifically showed that the same task depleted some people more than others. These differences may reflect differences in personality and values (as in Study 2) or in physiological capabilities and response patterns. We also assume, but have not shown, that different self-control tasks would be differentially depleting even to the same person in the same circumstances. At its core, self-regulatory change involves overriding one response in order to enable a different response. The stronger the initial response or impulse, the more difficult the self-control task will be—and, we would assume, the greater amount of energy in the form of blood glucose the system would have to expend in order to succeed.

Another implication is that self-control tasks that have a direct impact on blood glucose may raise particular problems for self-control. Most obviously, dieting essentially involves restricting one's caloric intake, and there may be an ironic conflict in which the dietary restriction produces lower glucose, which, in turn, undermines the willpower needed to refrain from eating. Further research in self-control may explore how efforts to control some behaviors paradoxically undercut the capacity for control by interfering with the body's glucose processes.

We do not wish to overstate the importance of glucose to self-control. Self-control may have multiple physiological and psychological links and processes. Sleep and rest, for example, seem beneficial to self-control independently of caloric processes (see Baumeister et al., 1994, for a review). Although it is possible that their effects could be mediated by glucose, they may signal that other factors can also be decisive. The present results nonetheless do point to glucose as important for self-control.

Moreover, despite our manipulations, we do not intend to advocate consuming large quantities of sugar as an ideal strategy for improving self-control. Eating several candy bars, for instance, may give one a boost of energy and better self-control, but these benefits are likely to disappear when glucose levels eventually drop. Protein or complex carbohydrates may be more effective for sustained self-control. We used sugar in our studies because it is fast-acting and convenient.

Concluding Remarks

It has long been known that action consumes energy. More recent evidence has indicated that some brain and cognitive processes likewise consume substantial amounts of energy—indeed, some far more than others. The "last-in, first-out rule" states that cognitive abilities that developed last ontogenetically are the first to become impaired when cognitive and physiological resources are compromised. Self-control, as a relatively advanced human capacity, was probably one of the last to develop and hence may be one of the first to suffer impairments when resources are inadequate. The present findings suggest that relatively small acts of self-control are sufficient to deplete the available supply of glucose, thereby impairing the control of thought and behavior, at least until the body can retrieve more glucose from its stores or ingest more calories. More generally, the body's variable ability to mobilize glucose may be an important determinant of people's capacity to live up to their ideals, pursue their goals, and realize their virtues.

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