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Motivational Versus Metabolic Effects of Carbohydrates on Self-Control

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Abstract

Self-control is critical for achievement and well-being. However, people's capacity for self-control is limited and becomes depleted through use. One prominent explanation for this depletion posits that self-control consumes energy through carbohydrate metabolization, which further suggests that ingesting carbohydrates improves self-control. Some evidence has supported this *energy model*, but because of its broad implications for efforts to improve self-control, we reevaluated the role of carbohydrates in self-control processes. In four experiments, we found that (a) exerting self-control did not increase carbohydrate metabolization, as assessed with highly precise measurements of blood glucose levels under carefully standardized conditions; (b) rinsing one's mouth with, but not ingesting, carbohydrate solutions immediately bolstered self-control; and (c) carbohydrate rinsing did not increase blood glucose. These findings challenge metabolic explanations for the role of carbohydrates in self-control depletion; we therefore propose an alternative *motivational model* for these and other previously observed effects of carbohydrates on self-control.

Keywords

self control, motivation, strength model of self-regulation, ego depletion, glucose, mental performance

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People's effortful regulation of their thoughts and actions—that is, their use of *self-control*—has an enormous impact on their lives. Studies have repeatedly demonstrated that the more self-control individuals typically exercise, the happier, healthier, and more successful they are in their professions and relationships from adolescence to old age (Mischel, Shoda, & Rodriguez, 1989; Moffitt et al., 2011; Tangney, Baumeister, & Boone, 2004). Accordingly, researchers have long worked to understand who engages in self-control and how people's self-control abilities can be improved (Baumeister, Gailliot, DeWall, & Oaten, 2006; Diamond, Barnett, Thomas, & Munro, 2007).

One primary challenge to improving self-control is that whenever people exert self-control, they appear to draw on a global pool of self-regulatory resources that is limited and therefore can be depleted. Using the metaphor of a muscle, researchers have likened the depletion of self-regulatory resources to the expenditure of energy during physical activity, which produces temporary fatigue and difficulty in sustaining attention and effort (Muraven & Baumeister, 2000). Consistent with this metaphor, results from a recent meta-analysis of 83 studies clearly demonstrated that following tasks requiring self-control or executive function, performance on subsequent tasks that also require self-control declines, even when the initial and subsequent tasks involve different modalities (e.g., perceptual monitoring vs. logical reasoning; Hagger, Wood, Stiff, & Chatzisarantis, 2010).

The Energy Model of Self-Control

The metaphorical conceptualization of self-control as a muscle whose effectiveness lessens with continued use has been enormously influential and has greatly advanced thinking and research on this topic. However, some researchers have recently argued that similarities between self-control processes and muscle function are not simply metaphorical (Gailliot & Baumeister, 2007): Studies have suggested that just as muscles metabolize simple carbohydrates as their primary fuel, self-control may also rely on carbohydrate metabolization (Gailliot et al., 2007; Gailliot, Peruche, Plant, & Baumeister, 2009; Masicampo & Baumeister, 2008). That is, these studies have

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implied that just as physical exertion consumes carbohydrates, exerting self-control depletes the body's carbohydrate stores, and just as physical activity can be bolstered when carbohydrates are ingested, self-control is also enhanced by carbohydrate intake.

This *energy model* of limited self-control has several wide-ranging implications. For example, individuals with inherited or acquired deficiencies in carbohydrate metabolization would presumably face great challenges in achieving success and well-being. Also, despite the current trend of eliminating carbohydrate-laden foods from school and office cafeterias, such foods could actually help sustain learning and productivity. Carefully evaluating this energy model of self-control is therefore broadly important for both public policy and public health and was the primary objective of the research reported here.

Challenges to the Energy Model of Self-Control

The idea that carbohydrate metabolization plays a role in self-control has not gone unchallenged (Beedie & Lane, 2012; Kurzban, 2010). In addition to questions about the methodology used to assess such metabolization, criticisms have focused on the physiological mechanisms proposed to explain how carbohydrate metabolization fuels self-control (also see Gibson, 2007; Messier, 2004). The specific goals of the present research were therefore (a) to test whether the behavioral effects of exerting self-control are linked to the metabolization of carbohydrates using a more precise methodology than has been used in previous work, and (b) to evaluate an alternative *motivational model* for explaining the link between the ingestion of carbohydrates and improved self-control.

Although the relationship between the availability of simple carbohydrates, such as glucose, in the blood and the utilization of these carbohydrates in the brain is not straightforward (Gibson, 2007; Messier, 2004), one piece of evidence for the energy model of limited self-control is that engaging in self-control appears to lower blood glucose levels (Dvorak & Simons, 2009; Gailliot et al., 2007). However, other studies have shown contradictory results (Kurzban, 2010). One reason for this inconsistency could be that studies linking carbohydrate metabolization to self-control have employed commercially available Accu-Chek blood glucose monitors (Roche Diagnostics, Basel, Switzerland), whose results are less precise than those of formal laboratory assessments (Beedie & Lane, 2012; Khan, Vasquez, Gray, Wians, & Kroll, 2006). Therefore, in Experiment 1, we evaluated how exerting self-control affects both subsequent self-control and blood glucose levels using best-practice laboratory methods.

A second piece of evidence for the energy model of self-control is that ingesting carbohydrates after performing a task that requires self-control improves performance on subsequent tasks that also require self-control. That is, carbohydrate consumption appears to replenish the resources depleted by initial self-control efforts and to sustain future efforts (DeWall, Baumeister, Gailliot, & Maner, 2008; Gailliot et al., 2007; Gailliot et al., 2009; Masicampo & Baumeister, 2008). Compared with findings that self-control reduces blood glucose, findings that carbohydrate consumption improves self-control have been more consistent, and these latter findings match results from other experiments demonstrating that carbohydrate ingestion boosts performance on mental and physical tasks (Messier, 2004; Riby, 2004). However, it is unclear whether these effects are truly due to connections between carbohydrate metabolization and brain function (Beedie & Lane, 2012; Gibson, 2007; Kurzban, 2010; Messier, 2004).

An Alternative to the Energy Model: Motivational Effects of Carbohydrates

Recently, several researchers have discovered an alternative mechanism by which carbohydrates influence physical effort. Multiple experiments have demonstrated that participants who briefly rinse their mouths with, but do not ingest, carbohydrate solutions during intense physical activity (e.g., cycling or running time trials) show significant increases in performance as compared with participants who rinse with placebo solutions containing noncarbohydrate sweeteners (Chambers, Bridge, & Jones, 2009; see Painelli, Nicastro, & Lancha, 2010). Indeed, one study demonstrated that carbohydrate rinsing had a greater effect on performance than carbohydrate ingestion did (Pottier, Bouckaert, Gilis, Roels, & Derave, 2010). These studies indicate that carbohydrates affect persistence and performance in nonenergetic ways.

Furthermore, neuroimaging studies have suggested a specific origin for these nonenergetic effects: Carbohydrate mouth rinses activate dopaminergic pathways in the striatum—a region of the brain associated with responses to rewards (Kringelbach, 2004)—whereas artificially sweetened noncarbohydrate mouth rinses do not (Chambers et al., 2009). Thus, the mere sensing of carbohydrates in the mouth, whether or not they are ingested, may signal the possibility of reward (i.e., the future availability of additional energy), which could motivate, rather than fuel, physical effort. In addition, because prolonged physical exertion requires self-control (Morsella, 2005), existing findings that carbohydrate ingestion boosts mental activity requiring self-control could also be explained by increases in people's motivation to perseverate rather than in their level of energy.

To test whether merely sensing carbohydrates in the mouth can motivate self-regulation, in Experiments 2 and 3, we examined how rinsing with a carbohydrate solution influences self-control. Whereas previous studies have included a 10- to 12-min delay between the ingestion of carbohydrates and secondary self-control tasks, to allow time for metabolization (Gailliot et al., 2007; Gailliot et al., 2009; Masicampo & Baumeister, 2008), in Experiments 2 and 3, the secondary self-control task was performed immediately after rinsing, before metabolization could possibly occur. In addition, to ensure the generalizability of the results, we used different, but equally well-validated, measures and manipulations of executive function and self-control in each experiment.

Finally, although Experiments 2 and 3 tested whether carbohydrate rinsing improved self-control, they did not examine whether simply rinsing one's mouth with carbohydrates increases blood glucose by inducing the release of endogenous stores. This question was therefore our focus in Experiment 4.

Experiment 1: Does Self-Control Consume Carbohydrates?

Method

Participants. Eighty-five college students (52 females, 33 males; mean age = 19.28 years, *SD* = 1.25) participated in return for course credit or payment. To control for initial blood glucose levels and potential glycemic responses, we (a) required that participants weigh at least 110 lb, (b) instructed participants to abstain from eating for 4 hr and from vigorous exercise for 24 hr before the experiment, and (c) ran the experiment between 4 p.m. and 7 p.m.

Procedure and materials. Participants first received a baseline assessment of their blood glucose and then performed a perceptual-vigilance task requiring either a low or a high level of self-control. After participants' blood glucose was reassessed, we had them complete an anagram task to measure their continued exertion of self-control.

To assess blood glucose both before and after the perceptual-vigilance task, we followed the laboratory reference procedures against which all commercial glucose monitors are tested for accuracy (Khan et al., 2006). Participants placed their hands on a heating pad for 2 min, after which a small sample of blood was taken from their finger via capillary puncture. These samples were analyzed in duplicate with a YSI 2700 Glucose/Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH), and glucose levels were calculated in milligrams per deciliter.

The perceptual-vigilance task was identical to tasks used in many previous studies of self-control depletion (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Hagger et al., 2010). All participants first received one page of text and were instructed to cross out every "e." Those participants assigned to the *low-depletion* condition next received another, similar page of text with the same instructions. Those participants assigned to the *high-depletion* condition received another page of text with a different set of instructions asking them to cross out every "e" that was neither adjacent to nor one letter removed from another vowel. Following these new rules required participants in the high-depletion condition to monitor the text more vigilantly than participants in the low-depletion condition did and to inhibit the practiced response instantiated by the initial rules, which increased their expenditure of self-control resources (Baumeister et al., 1998).

In keeping with many previous studies on self-control depletion (Muraven, Tice, & Baumeister, 1998; see Hagger et al., 2010), following the second blood glucose assessment, we had participants perform an anagram task to assess the effects of the perceptual-vigilance task on their subsequent self-control. In the anagram task, participants were instructed to generate as many words as they could from a set of seven letters. The amount of time participants persisted on the task was our primary measure of their continued self-control.

Results and discussion

Because time spent on the anagram task was skewed (skewness = 1.21), analyses were conducted on log-transformed times (Judd & McClelland, 1989), but for ease of exposition, raw means are reported here. Our results replicated those of previous research (Hagger et al., 2010): Participants in the high-depletion condition (M = 3.80 min, SD = 2.74) persisted less than participants in the low-depletion condition did (M = 4.60 min, SD = 2.41), $t(83) = 2.09$, $p = .04$, $d = 0.47$.

However, a 2 (condition: low depletion vs. high depletion) × 2 (glucose assessment: pretask vs. posttask) mixed analysis of variance (ANOVA) on blood glucose levels with repeated measures on the second factor revealed no main effect of condition and no Condition × Glucose Assessment interaction, $Fs(1, 83) < 2.05$, $ps > .16$. Thus, despite affecting subsequent persistence, initially exerting greater self-control did not lead to greater carbohydrate metabolization. Indeed, overall, there was a marginally significant increase in blood glucose levels between the pretask assessment (M = 81.27 mg/dl, SD = 7.49) and the posttask assessment (M = 82.39 mg/dl, SD = 8.68), $F(1, 83) = 2.94$, $p = .09$, $d = 0.19$. This increase could perhaps be explained by a task-related release of cortisol, which increases blood glucose (Miller & Tyrell, 1995), but it cannot be explained by the energy model, which predicts decreases in blood glucose following the exertion of self-control.

Finally, in contrast to the findings of Gailliot et al. (2007), neither absolute levels of blood glucose following the perceptual-vigilance task nor changes in blood glucose from before to after the task were significantly correlated with persistence on the anagram task in either condition, $rs < |.20|$, $ps > .17$. Thus, our results from Experiment 1, in which we employed the most sensitive measures of blood glucose available, add to existing questions about whether the depletion of self-control resources involves carbohydrate metabolization (Beedie & Lane, 2012; Kurzban, 2010), as proposed by the energy model.

Experiment 2: Must Carbohydrates Be Metabolized to Bolster Self-Control?

Our results from Experiment 1 failed to support the predictions of the energy model of self-control concerning the metabolization of carbohydrates during the exertion of self-control. In Experiment 2, we evaluated a second prediction of the energy model: that the ingestion of carbohydrates provides additional "fuel" for self-control and reduces the depletion of self-control resources. After performing a task that required either a low or a high level of self-control, participants rinsed their mouths with, but did not ingest, a solution flavored with either a carbohydrate-based sweetener or a noncarbohydrate-based sweetener. They then immediately performed a second task that required self-control. Any results showing that merely rinsing with carbohydrate solutions bolstered self-regulation would further challenge the energy model's account of carbohydrates' effects on self-control.

Method

Participants. Forty-five university students participated in return for course credit. Data from 1 participant were eliminated because the participant's responses on a baseline self-control measure were extreme (4.59 *SD* above the grand mean). The final sample therefore consisted of 44 participants (28 females, 16 males; mean age = 18.84 years, *SD* = 0.57). All participants abstained from eating for at least 4 hr prior to the experiment and took part between 9 a.m. and 12 p.m. or between 4 p.m. and 7 p.m. The time at which participants took part in the experiment had no moderating effects on any of the analyses reported (all *p*s > .28).

Procedure and materials. To control for baseline differences in self-control resources, we had participants begin the experiment by squeezing together the handles of a high-tension handgrip to suspend a wad of paper in the air for as long as possible. Persistence on this task despite growing discomfort has been widely used in previous studies as an index of self-control (Muraven & Slessareva, 2003; see Hagger et al., 2010).

Participants next completed the same perceptual-vigilance task used in Experiment 1, in either the low- or the high-depletion condition. Then, following previously established procedures (Chambers et al., 2009; see Painelli et al., 2010), we gave participants in the *carbohydrate-rinse* condition a cup containing 25 ml of a 6.4% table-sugar solution and gave participants in the *noncarbohydrate-rinse* condition a cup containing 25 ml of a 3.2% solution of Equal, a noncarbohydrate, aspartame-based sweetener approximately twice as sweet as sugar. Participants rinsed their mouths with all 25 ml of the solution for 5 s and then spit it back into the empty cup.

Immediately after rinsing, participants completed a second trial of the handgrip task; the duration of each participant's persistence on this task served as our measure of his or her self-control following the depletion and rinsing manipulations. Finally, participants completed the Brief Mood Introspection Scale (Mayer & Gaschke, 1988); rated the rinsing solution's sweetness, refreshingness, and tastiness, using scales from 1 (*very low*) to 7 (*very high*; α = .58); and reported what they thought was used to flavor the solution.

Results and discussion

Because persistence times were not highly skewed in this experiment (skewness = 0.75), untransformed data were used for all analyses (Judd & McClelland, 1989). A 2 (depletion: low vs. high) × 2 (rinse: carbohydrate vs. noncarbohydrate) between-participants analysis of covariance (ANCOVA) was performed on persistence times for the second handgrip task, with persistence times for the first handgrip task included as a covariate. Results revealed only a significant interaction, $F(1, 39) = 4.54$, $p = .04$.

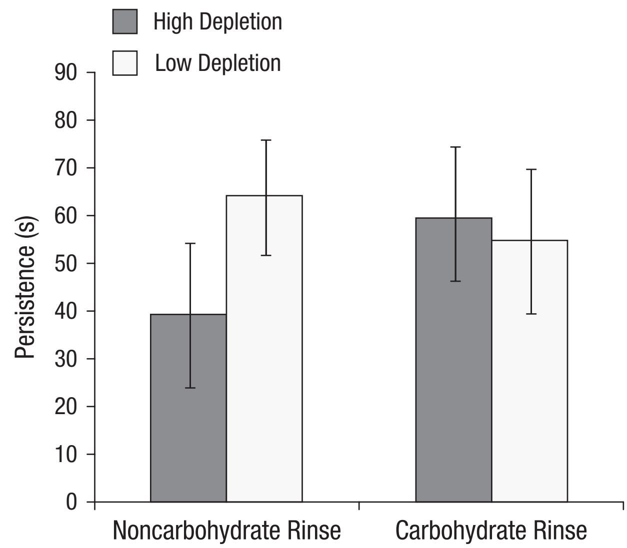

Fig. 1. Results from Experiment 2: participants' persistence in squeezing a handgrip immediately after rinsing their mouths for 5 s with a solution containing a noncarbohydrate-based sweetener or a carbohydrate-based sweetener. The rinse was administered after an initial perceptual-vigilance task that resulted in either a low or a high depletion of self-control resources. Error bars represent 95% confidence intervals.

Figure 1 shows that among participants who rinsed with the noncarbohydrate solution, those in the high-depletion condition displayed significantly reduced persistence compared with those in the low-depletion condition, $F(1, 39) = 6.60$, $p = .01$, $d = 0.77$, a result replicating the typically observed depletion of self-control after self-regulatory exertion (Hagger et al., 2010). However, there were no differences between the high- and low-depletion conditions among participants who rinsed with the carbohydrate solution, $F(1, 39) = 0.22$, $p = .64$, $d = 0.17$. Furthermore, in the high-depletion condition, rinsing with the carbohydrate solution produced significantly greater persistence than did rinsing with the noncarbohydrate solution, $F(1, 39) = 4.12$, $p = .05$, $d = 0.63$, whereas the rinsing manipulation had no effect in the low-depletion condition, $F(1, 39) = 0.90$, $p = .35$, $d = 0.28$. Thus, previous findings concerning the effects of carbohydrates on depleted self-control (Gailliot et al., 2007; Gailliot et al., 2009; Masicampo & Baumeister, 2008) were replicated in our experiment, even when carbohydrates were not ingested and when there was not sufficient time for them to be metabolized (cf. Chambers et al., 2009). Our results from Experiment 2 thus indicated that carbohydrates' effects on self-control are not necessarily related to metabolic consumption, as proposed by the energy model, and can operate through nonenergetic mechanisms.

Participants' mood and ratings of the taste of the solution did not differ across conditions, $Fs(1, 40) < 1.43$, $ps > .24$, *d*s < 0.36. Overall, when guessing what had been used to flavor the solution with which they had rinsed, 65% of participants said sugar, 23% said some other type of natural flavoring (e.g., fruit or tea), 7% said artificial sweetener, and 5% said they did not know. Guesses did not differ between participants who had rinsed with the sugar solution and those who had rinsed with the aspartame solution, $\chi^2(3, N = 44) = 4.83$, $p = .18$.

Experiment 3: Must Carbohydrates Be Metabolized to Bolster Cognitive as Well as Physical Self-Control?

Our results from Experiment 2 demonstrated that carbohydrate metabolism is not necessary for persistence on a physical task. In Experiment 3, we tested whether the same was true for persistence on a cognitive task.

Method

Participants. Thirty-one college students (22 females, 9 males; mean age = 18.58 years, $SD = 0.85$) participated in return for course credit. All participants abstained from eating for at least 4 hr prior to the experiment and took part between 9 a.m. and 12 p.m. or between 4 p.m. and 7 p.m. The time at which participants took part in the experiment had no moderating effects on any of the analyses reported (all *p*s > .16).

Procedure and materials. To control for baseline differences in self-control resources, we had participants begin the experiment by completing the color-word Stroop task (Stroop, 1935). This task involves identifying the color of letter strings as quickly and accurately as possible; on some trials, the letter strings form words for colors that are incongruent with the color in which the letters are displayed (e.g., the word "blue" displayed in red type), which creates response interference. The speed with which people overcome this interference has been widely used as a measure of executive function and self-control (Gailliot et al., 2007; Richeson, Baird, Gordon, Heatherton, & Wyland, 2003; see Hagger et al., 2010). The task consisted of 24 trials. Participants were instructed to press a response key whose color matched the color of the letters in each trial as quickly as possible without sacrificing accuracy. We calculated participants' Stroop-interference scores by subtracting each participant's mean response latency for trials on which letter strings did not form words (i.e., "xxxxxx") from his or her mean response latency for trials on which letter strings formed color words incongruent with the display color (Job, Dweck, & Walton, 2010; Richeson et al., 2003). Higher interference scores indicated greater failure to overcome response interference and thus less self-control.

Participants next performed a perceptual-vigilance task that has been frequently used in previous studies examining the depletion of self-control resources (Hagger et al., 2010; Schmeichel, Vohs, & Baumeister, 2003). In this task, participants watched a 6-min video that showed a woman speaking while a series of words appeared at the bottom of the screen for 10 s each. All participants were instructed to keep their attention focused on the woman's face instead of the words (i.e., to exert self-control to inhibit their natural orienting response). Previous research has demonstrated that performing this task induces a relatively high depletion of self-control resources (Hagger et al., 2010).

Next, participants rinsed with either a carbohydrate-sweetened or a noncarbohydrate-sweetened solution, following the same procedures used in Experiment 2. Immediately afterward, they completed 96 more trials of the Stroop task. Stroop-interference scores on these latter trials served as our primary measure of participants' self-control following the depletion and rinsing manipulations. Finally, participants completed the Brief Mood Introspection Scale and rated the taste of the solution with which they had rinsed, following the same procedures used in Experiment 2.

Results and discussion

Results are shown in Figure 2. Because Stroop-interference scores were not highly skewed (skewness = 0.69), untransformed data were used for all analyses. A one-way ANCOVA on participants' Stroop-interference scores from the second Stroop task, with scores from the first Stroop task included as a covariate, revealed that interference was significantly lower following carbohydrate rinsing than following noncarbohydrate rinsing, $F(1, 28) = 5.02$, $p = .03$, $d = 0.73$. Again, there were no differences between conditions in the valence or

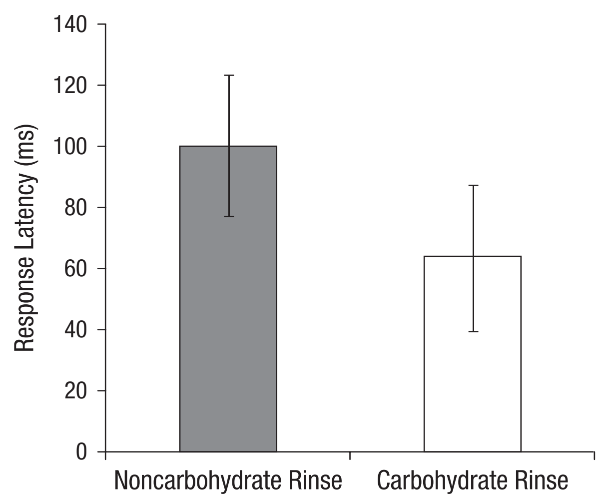

Fig. 2. Results from Experiment 3: mean response latencies for incongruent trials of the color-word Stroop task; the task was completed immediately after participants had rinsed their mouths for 5 s with a solution containing a noncarbohydrate-based or a carbohydrate-based sweetener. The rinse was administered after an initial perceptual-vigilance task that resulted in a high depletion of self-control resources. Error bars represent 95% confidence intervals.

arousal of participants' mood or in ratings of the taste of the solution, *F*s(1, 29) < 1.55, *p*s > .22, *d*s < 0.45. Our findings in Experiment 3 thus replicated those from Experiment 2; furthermore, given that the effects of carbohydrates on self-control emerged immediately and in the absence of ingestion, our results once again indicated that metabolization is not necessary for carbohydrates to bolster self-control, which runs contrary to the energy model of self-control.

Experiment 4: Does Rinsing With Carbohydrates Release Endogenous Energy Stores?

In Experiments 2 and 3, carbohydrates were never ingested and could not have been metabolized in the short time between rinsing and subsequent exertions of self-control; it is therefore likely that the observed effects of carbohydrates on self-control were due to nonenergetic mechanisms. However, rinsing one's mouth with carbohydrates could perhaps increase blood glucose by immediately prompting the release of endogenous carbohydrate stores. If this type of mechanism were responsible for the results of our experiments, our findings would still be broadly consistent with the energy model of self-control. Therefore, in Experiment 4, we directly tested the effects of rinsing with a carbohydrate solution on blood glucose levels.

Method

Participants. Twenty college students (11 females, 9 males; mean age = 19.30 years, *SD* = 1.26) participated in return for course credit or payment. As in Experiment 1, to control for initial blood glucose levels and potential glycemic responses, we (a) required that participants weigh at least 110 lb, (b) instructed participants to abstain from eating for 4 hr and from vigorous exercise for 24 hr before the experiment, and (c) ran the experiment between 4 p.m. and 7 p.m.

Procedure and materials. All participants received 350 ml of a 21.4% glucose (maltodextrin) solution. This solution was substantially greater in quantity and had a substantially greater concentration of glucose than the carbohydrate solution used in the previous experiments, and was designed to provide a strong test of the endogenous-release hypothesis. In the *ingest* condition, participants drank the entire volume of the solution. In the *rinse* condition, participants took a mouthful of the solution, swished it around for 5 s, and then spit it into an empty cup, repeating these steps until they had rinsed with the entire volume of the solution. Following ingestion or rinsing, participants completed unrelated filler tasks for 12 min. We assessed participants' blood glucose levels prior to rinsing or ingestion and after the 12-min delay using the same laboratory procedures used in Experiment 1.

Results and discussion

A 2 (condition: ingest vs. rinse) × 2 (glucose assessment: pretask vs. posttask) mixed ANOVA on blood glucose levels with repeated measures on the second factor revealed an interaction, *F*(1, 18) = 52.06, *p* < .001. Although, as expected, blood glucose increased substantially among participants who had ingested carbohydrates (pretask: *M* = 84.10 mg/dl, *SD* = 6.76; posttask: *M* = 113.97 mg/dl, *SD* = 15.69), *F*(1, 18) = 119.57, *p* < .001, *d* = 2.58, it did not increase among participants who had rinsed with the carbohydrate solution (pretask: *M* = 81.78 mg/dl, *SD* = 6.01; posttask: *M* = 83.78 mg/dl, *SD* = 9.23), *F*(1, 18) = 0.53, *p* = .47, *d* = 0.17.

General Discussion

Altogether, the results of the four experiments presented here challenge the energy model of self-control. Participants who exerted greater self-control persisted less on subsequent tasks but did not show any evidence of increased carbohydrate metabolization, as assessed using the most sensitive measures available. Furthermore, participants who rinsed their mouths with, but did not ingest, carbohydrate solutions showed immediate boosts in self-control, and rinsing itself did not increase blood glucose levels. These findings are all consistent with a motivational, rather than metabolic, role of carbohydrates in self-control (Painelli et al., 2010).

Although our results demonstrate that carbohydrate metabolization is not necessary to sustain self-control, they do not rule out the possibility that carbohydrate metabolization could benefit effort and performance in certain circumstances. It is also possible that sustained rinsing with carbohydrates has diminishing effects over time. However, given the inconsistent findings concerning the effect of mental effort on blood glucose levels, and the clear evidence for alternative mechanisms provided by our results and the results of prior work (Beedie & Lane, 2012; Kurzban, 2010; Painelli et al., 2010), we believe that a motivational rather than metabolic model of carbohydrates' effects on self-control offers a superior explanation for the available data.

An additional reason to favor motivational models is that many other findings concerning the depletion of self-control are also better explained by motivational models than by energy models. For example, studies have shown that the depleting effects of initial efforts at self-control are reversed by increased incentives for performance on subsequent tasks and by positive affect (Muraven & Slessareva, 2003; Tice, Baumeister, Shmueli, & Muraven, 2007). Depletion is also produced by mere perceptions of effortful expenditures of self-control (Clarkson, Hirt, Jia, & Alexander, 2010; Wan & Sternthal, 2008) and by expectations of future needs for self-control (Muraven, Shmueli, & Burkley, 2006), and it occurs only when people believe that their self-control abilities are limited (Job et al., 2010). Thus, although engaging in self-control often leaves people less willing to subsequently exert further self-control (or more conscious about conserving what they believe is a limited resource), it does not leave them without the energy to do so when properly motivated.

In conclusion, our results help to clarify the psychological and physiological mechanisms responsible for declining self-control following continued exertion, even when exertion is split between different tasks or goals. Findings indicating that this decline is better explained by deficits in motivation than by decreased energy or ability suggest the possibility of new, promising interventions. Indeed, interventions focused on sustaining or altering self-control motivations could be developed to increase people's self-control and thus improve outcomes throughout their lives.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

References

Baumeister, R. F., Bratslavsky, E., Muraven, M., & Tice, D. M. (1998). Ego depletion: Is the active self a limited resource? *Journal of Personality and Social Psychology*, *74*, 1252–1265.

Baumeister, R. F., Gailliot, M., DeWall, C. N., & Oaten, M. (2006). Self-regulation and personality: How interventions increase regulatory success, and how depletion moderates the effects of traits on behavior. *Journal of Personality*, *74*, 1773–1802.

Beedie, C. J., & Lane, A. M. (2012). The role of glucose in self-control: Another look at the evidence and an alternative conceptualization. *Personality and Social Psychology Review*, *16*, 143–153.

Chambers, E. S., Bridge, M. W., & Jones, D. A. (2009). Carbohydrate sensing in the human mouth: Effects on exercise performance and brain activity. *Journal of Physiology*, *587*, 1779–1794.

Clarkson, J. J., Hirt, E. R., Jia, L., & Alexander, M. B. (2010). When perception is more than reality: The effects of perceived versus actual resource depletion on self-regulatory behavior. *Journal of Personality and Social Psychology*, *98*, 29–46.

DeWall, C. N., Baumeister, R. F., Gailliot, M. T., & Maner, J. K. (2008). Depletion makes the heart grow less helpful: Helping as a function of self-regulatory energy and genetic relatedness. *Personality and Social Psychology Bulletin*, *34*, 1653–1662.

Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007). Preschool program improves cognitive control. *Science*, *318*, 1387–1388.

Dvorak, R. D., & Simons, J. S. (2009). Moderation of resource depletion in the self-control strength model: Differing effects of two modes of self-control. *Personality and Social Psychology Bulletin*, *35*, 572–583.

Gailliot, M. T., & Baumeister, R. F. (2007). The physiology of willpower: Linking blood glucose to self-control. *Personality and Social Psychology Review*, *11*, 303–327.

Gailliot, M. T., Baumeister, R. F., DeWall, C. N., Maner, J. K., Plant, E. A., Tice, D. M., . . . Schmeichel, B. J. (2007). Self-control relies on glucose as a limited energy source: Willpower is more than a metaphor. *Journal of Personality and Social Psychology*, *92*, 325–336.

Gailliot, M. T., Peruche, B. M., Plant, E. A., & Baumeister, R. F. (2009). Stereotypes and prejudice in the blood: Sucrose drinks reduce prejudice and stereotyping. *Journal of Experimental Social Psychology*, *45*, 288–290.

Gibson, E. L. (2007). Carbohydrates and mental function: Feeding or impeding the brain? *Nutrition Bulletin*, *32*, 71–83.

Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin*, *136*, 495–525.

Job, V., Dweck, C., & Walton, G. M. (2010). Ego depletion—is it all in your head? Implicit theories about willpower affect self-regulation. *Psychological Science*, *21*, 1686–1693.

Judd, C. M., & McClelland, G. H. (1989). *Data analysis: A model comparison approach*. New York, NY: Harcourt Brace Jovanovich.

Khan, A. I., Vasquez, Y., Gray, J., Wians, F. H., Jr., & Kroll, M. H. (2006). The variability of results between point-of-care testing glucose meters and the central laboratory analyzer. *Archives of Pathology & Laboratory Medicine*, *130*, 1527–1532.

Kringelbach, M. L. (2004). Food for thought: Hedonic experience beyond homeostasis in the human brain. *Neuroscience*, *126*, 807–819.

Kurzban, R. (2010). Does the brain consume additional glucose during self-control tasks? *Evolutionary Psychology*, *8*, 244–259.

Masicampo, E. J., & Baumeister, R. F. (2008). Toward a physiology of dual-process reasoning and judgment: Lemonade, willpower, and expensive rule-based analysis. *Psychological Science*, *19*, 255–260.

Mayer, J. D., & Gaschke, Y. N. (1988). The experience and meta-experience of mood. *Journal of Personality and Social Psychology*, *55*, 102–111.

Messier, C. (2004). Glucose improvement of memory: A review. *European Journal of Pharmacology*, *490*, 33–57.

Miller, W., & Tyrell, J. (1995). *Endocrinology and metabolism*. New York, NY: McGraw-Hill.

Mischel, W., Shoda, Y., & Rodriguez, M. I. (1989). Delay of gratification in children. *Science*, *244*, 933–938.

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, USA*, *108*, 2693–2698.

Morsella, E. (2005). The function of phenomenal states: Supramodular interaction theory. *Psychological Review*, *112*, 1000–1021.

Muraven, M., & Baumeister, R. F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle? *Psychological Bulletin*, *126*, 247–259.

Muraven, M., Shmueli, D., & Burkley, E. (2006). Conserving self-control strength. *Journal of Personality and Social Psychology*, *91*, 524–537.

Muraven, M., & Slessareva, E. (2003). Mechanisms of self-control failure: Motivation and limited resources. *Personality and Social Psychology Bulletin*, *29*, 894–906.

Muraven, M., Tice, D. M., & Baumeister, R. F. (1998). Self-control as limited resource: Regulatory depletion patterns. *Journal of Personality and Social Psychology*, *74*, 774–789.

Painelli, V. S., Nicastro, H., & Lancha, A. H., Jr. (2010). Carbohydrate mouth rinse: Does it improve endurance exercise performance? *Nutrition Journal*, *9*, 33.

Pottier, A., Bouckaert, J., Gilis, W., Roels, T., & Derave, W. (2010). Mouth rinse but not ingestion of a carbohydrate solution improves 1-h cycle time trial performance. *Scandinavian Journal of Medicine & Science in Sports*, *20*, 105–111.

Riby, L. M. (2004). The impact of age and task domain on cognitive performance: A meta-analytic review of the glucose facilitation effect. *Brain Impairment*, *5*, 145–165.

Richeson, J. A., Baird, A. A., Gordon, H. L., Heatherton, T. F., & Wyland, C. L. (2003). An fMRI investigation of the impact of interracial contact on executive function. *Nature Neuroscience*, *6*, 1323–1328.

Schmeichel, B. J., Vohs, K. D., & Baumeister, R. F. (2003). Intellectual performance and ego depletion: Role of the self in logical reasoning and other information processing. *Journal of Personality and Social Psychology*, *85*, 33–46.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality*, *72*, 271–324.

Tice, D. M., Baumeister, R. F., Shmueli, D., & Muraven, M. (2007). Restoring the self: Positive affect helps improve self-regulation following ego depletion. *Journal of Experimental Social Psychology*, *43*, 379–384.

Wan, E. W., & Sternthal, B. (2008). Regulating the effects of depletion through monitoring. *Personality and Social Psychology Bulletin*, *34*, 32–46.