THE PATHWAY FROM SUGAR TO SELF-CONTROL

A Dissertation

by

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ABSTRACT

The role of glucose in self-control has been under heated debate. Recent studies have suggested that both swishing and ingesting glucose can improve self-control, casting doubt on the idea that reduced self-control results from depleted blood glucose levels. However, no studies have directly compared the effects of rinsing and ingesting glucose on self-control. Furthermore, despite a multitude of behavioral evidence that glucose restores self-control, the mechanisms behind this restoration effect remain unknown. In two studies examining the effects of glucose on self-control, participants received one of three beverages that contained either glucose or aspartame. Two of the beverages were identical glucose solutions, but one group ingested it and the other group rinsed their mouths with the liquid and spit it out.

In the first study participants completed a task that did or did not require the use of self-control before being asked to drink or swish the beverage. Participants then completed a series of tasks to assess self-control, emotional responding, and future discounting. Among participants who exerted self-control, both swishing and ingesting glucose solutions improved subsequent self-control performance. Furthermore, swishing glucose increased self-reported arousal to all images and reduced discounting of future rewards.

The design for Study 2 was nearly identical to Study 1, except that all participants exerted self-control on the initial task, the tasks were counterbalanced in a different order, and participants no longer rated their subjective reactions to the

emotional images. Instead, electroencephalography was used to assess emotional processing as well as various cognitive processes occurring before and after responses on the dependent measure of self-control. Both glucose conditions caused lower emotional processing for all image types, contrasting with Study 1. No effects of drinking glucose were found for self-control or future discounting, due in part to insufficient sample size. Emotional reactions were linked to self-control performance. Furthermore, blood glucose levels were related to action monitoring processes following self-control failure, despite not predicting self-control performance in either study. These results include some of the first direct evidence of processes affected by glucose following self-control exertion and provide a glimpse into the underlying mechanisms behind self-control restoration.

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CHAPTER I

INTRODUCTION

The human capacity for self-control has received increasing research attention in the past decade, which is not surprising given its utility. Most theorists agree that self-control involves altering (e.g., stopping, modifying, or replacing) an impulsive or habitual response tendency (Baumeister, Heatherton, & Tice, 1994). Whether it is resisting the temptation to eat an unhealthy dessert or fighting off the oppressive urges of a drug addiction, self-control is a valuable asset that increases behavioral flexibility and facilitates the pursuit of distant or higher-level goals.

Valuable assets are often limited, and this also appears to be the case with self-control. Research suggests that the capacity to override impulses can only be used for a limited period of time before it declines. This effect has been termed the ego depletion effect (Baumeister, Vohs, & Tice, 2007) and has been replicated in numerous studies, such that individuals who engage in one self-control task perform worse on a subsequent self-control task, even if the two tasks are otherwise unrelated (e.g., Muraven & Baumeister, 2000; Muraven, Tice, & Baumeister, 1998; Schmeichel & Baumeister, 2004).

This reliable pattern of results has led researchers to conclude that all self-control draws upon a single limited resource that functions like a muscle and grows fatigued with use (Muraven & Baumeister, 2000). But what is the resource? Based on the fact that the body and the brain both rely on the metabolism of glucose for energy, Gailliot

and colleagues (2007) proposed that glucose serves as the physiological resource fueling self-control. They reported evidence that acts of self-control deplete blood glucose levels, and that the lower glucose levels predict the decrease in self-control capacity stemming from ego depletion.

As reviewed below, the claim that glucose enables self-control was both influential and controversial. Many researchers questioned whether completing a brief self-control task could cause a deficit in glucose. Indeed, some studies have failed to find that exercising self-control depletes blood glucose levels (e.g., Molden et al., 2012), casting doubt on the idea that drops in blood glucose are responsible for the ego depletion effect. Other studies have found that merely swishing glucose in the mouth and spitting it out – without digesting and metabolizing it – is sufficient to restore self-control following depletion (e.g., Hagger & Chatzisarantis, 2013), thereby weakening the argument for a resource model based on glucose. Nevertheless, evidence has continued to accumulate suggesting that administering glucose can improve self-control, and alternative models have arisen to explain the ego depletion effect and the role of glucose in self-control. However, few models have identified specific mechanisms for either the depletion or the replenishment of what appears to be a limited resource underlying self-control. The current investigation combines measures of blood glucose, cognitive performance, and electroencephalography (EEG) to find evidence for specific processes underlying the effects of sugar on self-control.

CHAPTER II

RESOURCE MODEL OF SELF-CONTROL

The term “ego depletion” was coined by the proponents of the resource model (also known as the strength or energy model) of self-control to suggest that willpower relies on an internal energy source that is used when one engages in self-control (Baumeister & heatherton, 1996; Baumeister, heatherton, & Tice, 1994; Muraven & Baumeister, 2000). The basic ego depletion effect has been replicated over a hundred times across various self-control tasks (see Hagger, Wood, Stiff, & Chatzisarantis, 2010). For example, down-regulating emotional responses in the first phase of an experiment has been found to reduce persistence and physical stamina on subsequent tasks (Muraven et al., 1998). The opposite form of emotion regulation, namely up-regulating or exaggerating emotions, has been found to cause poorer performance on a cognitive fluency task afterwards (Schmeichel, Demaree, Robinson, & Pu, 2006). These studies and many others have repeatedly found that tasks requiring the alteration of a response appear to deplete a limited inner resource, compared to similar tasks that do not require self-control.

Neural underpinnings of ego depletion

The vast majority of research on the resource model has sought to document the ego depletion effect using different behavioral tasks as depletion manipulations and as dependent measures, but relatively few studies have provided strong evidence for the mechanisms behind self-control depletion. One approach to studying the relevant

mechanisms behind the behavioral evidence for ego depletion is to examine brain responses during self-control tasks. This method allows researchers to identify brain regions and networks that are responsible for enacting self-control, and perhaps more importantly, to identify regions related to self-control deficits.

Only a few studies have examined brain responses in the context of ego depletion. Two studies assessed the effect of ego depletion on the error-related negativity (ERN), a neural signal assessed using EEG that is especially large after making a mistake. The ERN is thought to be generated by the anterior cingulate cortex (ACC; Kiehl, Liddle, & Hopfinger, 2000) and may serve as a neurological index of action monitoring (see Falkenstein, Hoormann, Christ, & Hohnsbein, 2000). Exercising self-control to suppress emotions on an initial task has been found to reduce ERNs on a subsequent Stroop task (Wang & Yang, 2014), and reduced ERNs have been found to mediate the decrements in Stroop performance stemming from ego depletion (Inzlicht & Gutsell, 2007). These patterns suggest that after exercising self-control, the capacity to monitor action is reduced.

Conceptually similar studies have been conducted using functional magnetic resonance imaging (fMRI) in an attempt to pinpoint specific brain regions affected by using self-control. One such study had participants exercise self-control to suppress emotions before completing a Stroop task (Friese, Binder, Luechinger, Boesiger, & Rasch, 2013). Exercising self-control did not affect activity in the dorsal ACC (the proposed generator for the ERN) during the Stroop task but did reduce activity in the

right dorsolateral prefrontal cortex (DLPFC), a region thought to be responsible for top-down, effortful control (Cohen, Berkman, & Lieberman, 2013; Lieberman, 2007).

Other recent fMRI studies induced ego depletion by instructing participants to ignore words appearing on-screen during a video presentation. Afterwards, brain activity was measured while participants viewed negative emotional images (Wagner & Heatherton, 2013) or images of delicious foods (in a sample of dieters; Wagner, et al., 2013). Both studies found increased activity in emotional centers of the brain (i.e., amygdala and orbitofrontal cortex) in response to the target images among those who had previously exercised self-control. Prior efforts at self-control did not appear to influence subsequent activity in the DLPFC, but Wagner et al. reported less functional connectivity between the DLPFC and the emotional regions after participants had exercised self-control. Thus, both studies found greater neural reactivity associated with emotional responding under ego depletion, and one study found evidence of weaker reciprocal influence between brain regions implicated in emotions and top-down control.

The evidence from EEG and fMRI studies points to possible mechanisms underlying the behavioral aftereffects of exerting self-control. Reductions in self-control may be caused by reduced functionality of the processes necessary for overriding a dominant response. This perspective is consistent with both the strength model view that the capacity for control is reduced under ego depletion, and with evidence from EEG studies that have observed reduced action monitoring (i.e., reduced ERN magnitudes) after effortful acts of self-control. Alternatively, it may be the case that dominant response tendencies that would otherwise be suppressed are intensified after initial

efforts at self-control. This possibility is supported by evidence that neural regions associated with reward show increased activation to appetitive stimuli after effortful acts of self-control (Wagner, Altman, Boswell, Kelley, & Heatherton, 2013; Wagner & Heatherton, 2013). It is also possible that other (e.g., emotional) factors influence motivational processes that reduce the participants' desire to engage in self-control. Perhaps the most likely explanation is that the ego depletion effect reflects some mixture of each of these processes. In addition to understanding how self-control can be depleted, neural evidence also suggests starting points for understanding how self-control may be restored.

CHAPTER III

RESTORING DEPLETED SELF-CONTROL

Muraven and Baumeister (2000) likened self-control to a muscle because the evidence for diminished self-control after prior use follows a similar pattern as tired muscles. However, whereas the metabolic processes underlying muscle activity are relatively clear, it is currently unknown what fuels self-control. Given its central role as a source of energy for bodily and brain functions, glucose seemed to be a logical starting point, and some evidence suggests that consuming glucose can restore self-control under ego depletion.

Evidence for glucose as a resource

Several lines of evidence have suggested that glucose improves performance on tasks that require self-control. For instance, consuming glucose has been found to speed up responses on the Stroop color-word interference task without causing a corresponding drop in accuracy (Benton, Owens, & Parker, 1994, Study 2). Consuming glucose has also been found to facilitate rapid responses and attentional focus on other cognitive tasks (Jones, Sünran-Lea, & Wesnes, 2012), including tasks that require controlled processing. For instance, individuals who had consumed glucose (versus aspartame) performed better (i.e., responded more quickly without making more errors) on a flanker task (Brandt, Gibson, & Rackie, 2013). However, another study found the opposite pattern of results, such that glucose consumption slowed responses on a flanker task (Hope, Seiss, Dean, Williams, & Sterr, 2013). These findings are relevant to

understanding self-control insofar as the Stroop and flanker tasks, by requiring participants to ignore salient stimuli to produce a correct response, require the exertion of cognitive control. The beneficial effects of consuming glucose have also been observed in many other self-control tasks, including future discounting (Wang & Dvorak, 2010), sharing behavior (Aarøe & Petersen, 2013), and regulating prejudices and stereotypes (Gailliot, Peruche, Plant, & Baumeister, 2009).

One study found that consuming glucose facilitated performance on a working memory task, and declining glucose levels (after the initial spike) predicted better performance (Martin & Benton, 1999), hinting at the possibility that the demanding memory task consumed glucose. Extending this line of thinking, Fairclough and Houston (2004) administered two versions of the Stroop task and found that participants who completed a version of the task including only incongruent trials (requiring control processes) showed a greater decrease in blood glucose levels compared to those who completed a version including only congruent trials (requiring automatic processes). This finding suggested that cognitive processes requiring self-control may require more glucose than other processes.

Following Fairclough and Houston (2004) an influential series of studies found that self-control tasks consume glucose to a greater extent compared to other cognitive tasks (Gailliot et al., 2007). For example, Gailliot et al. showed participants a video with words occasionally appearing on a corner of the screen, and found that pointedly ignoring the words caused bigger drops in blood glucose levels compared to viewing the video normally. Furthermore, drops in blood glucose levels predicted the behavioral

aftereffects (e.g., poorer Stroop performance) associated with ego depletion. Last, they found evidence that ingesting glucose appeared to replenish self-control capacity following ego depletion. For example, suppressing emotions led to reduced persistence on a frustrating task, unless participants consumed a glucose-rich beverage before the frustrating task. Taken together, the findings reported by Gailliot et al. strongly implicated glucose as a physiological basis for the limited resource for self-control.

Several independent researchers have attempted to replicate elements of the Gailliot et al. (2007) findings. One study successfully replicated the evidence that the ego depletion effect is predicted, and even (partially) mediated by drops in blood glucose levels (Dvorak & Simons, 2009), supporting the idea that drops in glucose are related to reduced self-control capacity. In addition, other studies found that behaviors that wane under ego depletion are restored after glucose ingestion, such as helpful behavior (De Wall, Baumeister, Gailliot, & Maner, 2008; Xu, Bègue, Sauve, & Bushman, 2014).

A now decade-old meta-analysis calculated the effect size for glucose administration on cognitive performance and found a moderate-sized effect (Riby, 2004). A more recent meta-analysis (Hagger et al., 2010) found that the effect size for glucose administration on self-control tasks specifically was $d = 0.75$ (95% CI [0.48, 1.03]), a large effect by common standards (Cohen, 1987). Altogether, the evidence reviewed in this section supports a causal link between glucose consumption and self-control, lending support to the idea that the brain draws upon glucose as a resource for self-control (Gailliot & Baumeister, 2007; Gailliot et al., 2007).

Evidence against glucose as a resource

The glucose evidence, in combination with the resource model of self-control, suggests that self-control requires a certain level of glucose in the bloodstream ready for the brain to use. Although evidence that participants perform better at self-control tasks after ingesting more of the purported "fuel" supports this claim, other studies have found alternative methods of preventing or reversing the ego depletion effect without giving participants sugar. These studies call into question the necessity of glucose for good self-control.

Multiple studies from independent sources have found that incentives for good performance eliminate the ego depletion effect (Boksem, Meijman, & Lorist, 2006; Muraven & Slessareva, 2003; Schmidt et al., 2012). That is, simply providing a reason for maintaining good performance (e.g., with rewards) appears to motivate depleted participants to perform well on a subsequent task. Other studies have found similar results by showing participants a comedy video or giving them a surprise gift (Tice, Baumeister, Shmueli, Muraven, 2007). Even showing depleted participants images of natural scenery has been found to restore self-control (Beute & de Kort, 2014). Many other manipulations have been observed to accomplish the same outcome, from affirming core values (Schmeichel & Vohs, 2009) to smoking cigarettes (Heckman, Ditre, & Brandon, 2012). These findings are difficult to explain from a limited resource point of view because it is not obvious how these interventions would restore a glucose-based resource.

Perhaps the most convincing arguments against glucose as a self-control energy source came from Kurzban (2010), who reviewed evidence refuting several assumptions that are necessary to support a resource model of self-control. First, if self-control is fueled by glucose, then using self-control must reduce glucose levels more than a task not using self-control. Kurzban (2010) reanalyzed the data reported by Gailliot et al. (2007) on this point and was unable to reproduce the original findings. Several laboratories have also been unable to replicate the finding that tasks requiring self-control deplete more glucose relative to other tasks. For example, one study had participants perform an attention-demanding continuous performance test (AX-CPT) for 90 minutes or had participants simply watch videos for the same amount of time. Those who completed the AX-CPT did not show a greater reduction in blood glucose levels compared to the control group (Marcora, Statiano, & Manning, 2009). Thus, using self-control did not influence blood glucose levels more than completing a passive viewing task.

In addition, although brain functions require energy derived from glucose, no simple linear relationship exists between mental effort and glucose expenditure (Gibson, 2007; Messier, 2004). Even if it were the case that more effortful tasks consumed more glucose from the bloodstream, the amount of glucose needed for normal cognitive functions (including self-control tasks) is minimal, amounting to less than the calories contained in some of the placebo substances used in certain studies, including the influential studies of Gailliot et al. (2007) (see Kurzban, 2010). Lastly, there is no perfect relationship between glucose in the brain and glucose in the bloodstream

(Raichle & Mintun, 2006), though the majority of studies on the glucose-consuming effects of self-control have involved measures of glucose levels in the bloodstream acquired from the periphery (e.g., fingertips).

Perhaps taking inspiration from Kurzban's (2010) critique, direct evidence refuting the glucose-as-willpower hypothesis emerged shortly thereafter. In an attempt to ascertain the metabolic versus motivational effects of glucose, Molden and colleagues (2012) used highly precise laboratory measures of blood glucose levels and failed to find an effect of exercising self-control on carbohydrate metabolization. Furthermore, they found that having participants swish and spit out a glucose-sweetened drink reversed the ego depletion effect for both physical and cognitive measures of self-control. Specifically, following an ego depletion manipulation, swishing glucose led to more persistence on a hand-grip task (Study 2) and reduced interference on the Stroop task (Study 3) relative to swishing a sweet non-glucose solution. Other studies have replicated these patterns, finding that swishing glucose improves performance on a working memory task (Carter & McCollough, 2013) and other self-control tasks (Hagger & Chatzisarantis, 2013) following prior exertions of self-control.

Though proponents of the glucose-as-willpower view may suggest that a small portion of glucose is ingested even from swishing, rinsing the mouth with glucose versus aspartame does not appear to influence blood glucose levels, as indexed by highly precise glucose lactate measurements (Molden et al., 2012, Study 4) or by insulin responses (Teff, Devine, & Engelman, 1995). Furthermore, a conceptual replication of the Molden et al. swishing study found evidence for beneficial effects of swishing

glucose during (not before) the second self-control task (Sanders, Shirk, Burgin, & Martin, 2012). Given that glucose takes approximately 10 minutes to metabolize to the brain (Donohoe & Benton, 1999), the self-control benefits of swishing in this study could not have been due to energy supplied by glucose. Thus, although glucose is a vital energy source for the body and brain, the metabolism of glucose does not appear to be necessary to enhance self-control. Merely rinsing the mouth with glucose is enough to eliminate the ego depletion effect.

Alternative explanations

Given the growing evidence against a pure resource model of self-control, some theorists have provided alternative accounts for the many variables that restore self-control from the putative depleted state. If glucose stores are not significantly depleted (i.e., to a point of crisis) by exerting self-control, and the replenishment of glucose stores is not necessary to restore self-control, then why does self-control appear to be depleted? After all, if a muscle has ample energy available for effective functioning, then it should be able to contract with the desired force.

Beedie and Lane (2012) proposed a *resource allocation model*, which suggests that humans are capable of directing limited resources strategically to address goal-relevant needs. In this view self-control is still possible after prior exertion, but the energy necessary to maintain self-control may be allocated towards something else insofar as individuals are no longer motivated to exert control to the same degree. For example, an individual may resist a tempting cupcake, but if they anticipate having to

exert additional effort in the future, they may give in to temptation and eat it. Such a strategy may help to conserve energy resources for future challenges.

Evidence for putative resource conservation has been observed in experiments in which participants are given three self-control tasks to perform. In one set of experiments, half of the participants were told they would later have to do a third difficult self-control task, and those participants performed worse on the second task but performed better on the subsequent (third) self-control task compared to those who were not warned of a third self-control task (Muraven, Shmueli, & Burkley, 2006). This pattern provides evidence that participants who had been warned of an impending challenge conserve resources for later use. The resource allocation model also accounts well for other studies that have found restored self-control among participants who were incentivized to perform well, such that even presumably depleted participants allocated more energy to an effortful task if they had a compelling reason to do so (e.g., Boksem, Meijman, & Lorist, 2006; Muraven & Slessareva, 2003; Schmidt et al., 2012).

Many models of self-control fatigue tend to agree that motivation (including the drive to conserve energy and the drive to obtain rewards) plays a central role in what appears to be resource depletion and its restoration (Molden et al., 2012; see Robert & Hockey, 1997 for a review). Most of these models explicitly reject the connection between a decline in self-control and the depletion of glucose levels in the bloodstream. However, there are also some discrepancies among the different models on the nature of the underlying processes relating to depletion. Some theorists have drawn from economic models of opportunity costs, claiming that individuals calculate the effort

needed for a task to determine whether that effort could be better used doing something else (Kurzban, Duckworth, Kable, & Myers, 2013). Other theorists have suggested that very little computation actually occurs but that motivational priorities switch from "have-to" goals (e.g., obligations) to "want-to" goals (i.e., leisure) following the use of self-control (Inzlicht, Schmeichel, Macrae 2014), possibly due to a shift in valuation of the different response options (Inzlicht et al., in press). No matter the process, several researchers agree that ego depletion is not a matter of inability or low glucose, but rather of shifting priorities.

CHAPTER IV

NEURAL UNDERPINNINGS OF GLUCOSE EFFECTS

Even if glucose is not the energy source underlying the resource model of self-control, administering glucose may yet be useful for determining the processes underlying self-control depletion and its restoration. Despite studies rebutting the ideas that a) exerting self-control reduces blood glucose and b) blood glucose levels mediate the depletion of self-control capacity, administering glucose nevertheless influences self-control performance. Furthermore, there is much evidence pertaining to the effects of glucose on neural activity that may be useful in divining the process by which glucose consumption influences self-control.

Drinking or briefly rinsing with a glucose-sweetened beverage both appear to undo the ego depletion effect. There are a few possible explanations for this pattern. The first and arguably the most intuitive explanation is that glucose improves the ability to exert self-control. Baseline glucose metabolism has been related to activity in the ACC and right fronto-temporal regions of the brain, and these regions have been associated with self-control (Pizzagalli, Oakes, & Davidson, 2003; see Banfield, Wyland, Macrae, Münte, & Heatherton, 2004). Also, glucose (but not artificial sweeteners) has been found to activate oral receptors that stimulate brain regions associated with motor control, action monitoring (Chambers, Bridge, & Jones, 2009; Jeukendrup & Chambers, 2010), and sensory perception (Chambers, Bridge, & Jones, 2009; Jeukendrup & Chambers,

2010; Turner, Byblow, Stinear, & Gant, 2014), and these changes in brain activity may benefit self-control ability.

Another possibility is that glucose influences reward processing and motivation to complete tasks. Glucose activates the brain's reward circuitry (Hommel et al., 2006; Volkow & Wise, 2005) in a manner akin to some recreational drugs (Avena, Rada, & Hoebel, 2008), and glucose-sensitive oral receptors that link to motor control and action monitoring also stimulate brain regions related to reward and motivation (Chambers et al., 2009; Jeukendrup & Chambers, 2010). Accordingly, a glucose rinse has been found to increase activity in the striatum (a region associated with reward; Kringelbach, 2004). Glucose may thus signal a heightened reward value of the task completed in proximity to glucose administration (Hagger & Chatzisarantis, 2013), which may reduce the aversiveness of the task and increase task motivation.

In addition, the ego depletion effect may be due in part to participants feeling as though they have fulfilled their obligation to the study or the experimenter by exercising self-control on the first task, and this feeling may justify "slacking off" for the rest of the study (Inzlicht & Schmeichel, 2012). Providing glucose to participants may serve as a type of compensation for working hard on the initial task, thereby motivating participants to perform well on subsequent tasks. Similarly, glucose may signal that resources are (imminently) abundant, which may give license for the allocation of resources toward self-control tasks (Beedie & Lane, 2012).

Glucose also influences brain regions related to the experience of emotions, including limbic circuits (Turner, Byblow, Stinear, & Gant, 2014). Assuming that

emotions influence self-control and self-control exertion (Schmeichel & Inzlicht, 2013), glucose may influence self-control by influencing emotions. For instance, glucose could reduce the aversiveness of self-regulatory exertion (by inhibiting negative affect or increasing positive affect), or it may increase conflict-related negative affect that has been found to facilitate cognitive effort (e.g., Saunders & Inzlicht, in press), either of which could serve to enhance self-control. Hagger and Chatzisarantis (2013) suggested that glucose consumption may enhance self-control by stimulating the ACC or the dopaminergic system of the ventral striatum. Although glucose ingestion may stimulate multiple areas of the brain, it is unclear whether the effects of glucose on self-control are limited to one or several neural circuits and whether the neural effects of consuming glucose differ from the effects of swishing glucose.

Source of the neural signal

Although evidence from glucose swish studies suggests that the detection of glucose by oral receptors is sufficient to reverse the ego depletion effect, no studies have directly compared the effects of swishing versus ingesting glucose. Thus, it is unknown whether ingesting glucose affects self-control above and beyond the effects of swishing glucose. Even after oral receptors send signals to the brain that reduce ego depletion, the pancreas or liver may send further signals to the brain (Gibson & Green, 2002; Messier, 2004) after glucose consumption that provide matching or additive effects to self-control that do not occur when glucose is merely swished. A recent study provided support for this possibility insofar as glucose and fructose, which are processed by the liver, had

similar effects on task persistence even though fructose does not influence blood glucose levels (Miller, Bourrasseau, & Blampain, 2013).

CHAPTER V

DISSERTATION STUDY I

Despite taking issue with a literal resource account, many researchers have presented alternative models using similar language. For instance, instead of referring to resources being depleted, some models suggest that participants run out of motivation. Although most theorists would agree that motivation is important for self-control, Young (1961) cautioned that general motivation by itself should not be considered a driving force for behavior; we cannot simply substitute motivation for glucose as the fuel for self-control. Instead, we should focus on specific processes influenced by ego depletion. This includes all the processes that underlie the initiation, maintenance, and regulation of action (Hockey, 1997) including attentional, emotional, and motivational processes.

To begin to isolate the processes underlying the effect of glucose administration on self-control, the current study sought to systematically replicate and extend past studies. We paired physiological measures with behavioral ones and also compared the effects of glucose ingestion versus swishing on blood glucose levels and self-control performance. In this way we hoped to provide concrete evidence for the role of oral (or otherwise located) glucose receptors versus glucose metabolism on self-control, in addition to identifying possible mechanisms of self-control failure and replenishment of regulatory processes.

We conducted an initial study in which we manipulated the requirement to exercise self-control on an initial task. Then we gave participants a beverage sweetened

with sugar or aspartame to consume, or we asked them simply to swish the sugar beverage in their mouth and spit it out. After a break period to allow the digestion of glucose, participants completed tasks to assess future discounting, reactivity to emotional stimuli, and self-control. This allowed us to assess behavioral indexes of reward valuation and sensitivity, emotional reactivity, and shifts in the operation of control mechanisms, respectively—potential mechanisms of ego depletion and glucose consumption effects that have been suggested by previous research. This initial study also paved the way for a subsequent study including measures of electrical activity in the brain.

We tested six hypotheses: (1) completing a controlled writing task will not reduce blood glucose more than completing a free writing task, (2) consuming glucose will increase measured blood glucose levels relative to swishing glucose and consuming aspartame, (3) glucose (vs. aspartame) will alter self-reported reactivity to emotional pictures, (4) glucose (vs. aspartame) will reduce future discounting, (5) glucose (vs. aspartame) will improve performance on the flanker task, and (6) blood glucose levels will not predict flanker performance, future discounting, or emotional reactivity. The implication of the last hypothesis is that glucose sensing (either via drinking or swishing), not the metabolic energy supplied by glucose, is chiefly responsible for the effects of glucose on self-control.

We also anticipated that swishing glucose would produce the same effects as ingesting glucose (relative to aspartame), though the effects of swishing versus ingesting glucose may differ in magnitude, such that the glucose ingestion effects surpass the

glucose swish effects (possibly due to additional contributions of the pancreas or liver in the glucose ingestion condition). We therefore conducted analyses contrasting glucose swishing versus glucose ingestion.

In addition, we conducted several exploratory analyses without *a priori* predictions. First, regarding the flanker task, "better performance" may be apparent in reaction time, response accuracy, or post-error slowing. We did not make specific predictions about which area(s) would be most improved by the glucose manipulation, nor which facets of performance would relate to other tasks. For the picture viewing task, we had competing hypotheses about the direction of glucose's effect on self-reported emotional responding. Glucose may a) activate reward regions of the brain (Kringelbach, 2004), resulting in greater reactivity to appetitive images and possibly also reduced reactivity to aversive images, b) increase conflict-related negative affect (Saunders & Inzlicht, in press), which may potentiate responding to aversive images, or c) reduce affective responding, limiting the appetitive and aversive contributions to self-control failure. Lastly, we explored the interrelationships among the major dependent variables included in the study, namely flanker performance, emotional reactivity to pictures, and future discounting.

CHAPTER VI

METHOD

Participants

One hundred fifty-three undergraduate students (56 men, 85 women, 12 unreported) completed a laboratory experiment investigating the effects of sweeteners and sugar on cognitive ability and decision-making. They received credit toward a psychology course requirement for participating. All participants were asked to refrain from eating for 4 hours prior to the experiment, to help to ensure equivalent levels of blood glucose levels at the start of the experiment. Exclusion criteria included diabetes or other blood-related diseases. Eight additional students participated in the study but were excluded from analyses: three were excluded for reporting they had diabetes, four participants declined to finish the entire study, and one participant was excluded for being aware of the purpose of the study.

Procedure and materials

Participants were randomly assigned to condition in a 2 (free writing vs. controlled writing) x 3 (glucose ingest, aspartame ingest, glucose swish) between-subjects design. After providing informed consent participants completed several personality questionnaires. Next, they completed a writing task that did versus did not require them to exercise self-control, and then they received a beverage to drink or swish. After the beverage manipulation, participants completed another set of questionnaires to allow for any glucose to be metabolized. Then participants viewed

IAPS pictures and completed a future discounting task (the order of these tasks was counterbalanced across participants) before completing a flanker task (the flanker task was administered last because it required the use of self-control, and we wanted to avoid additional self-control exertions before administering the other measures). Baseline blood glucose measurements were taken right before (T1) and right after the writing task (T2) to assess changes in blood glucose due to exercising self-control, as well as following a short delay after the beverage (T3) to asses changes in blood glucose following the beverage manipulation). See Figure 1 for a diagram of the procedure.

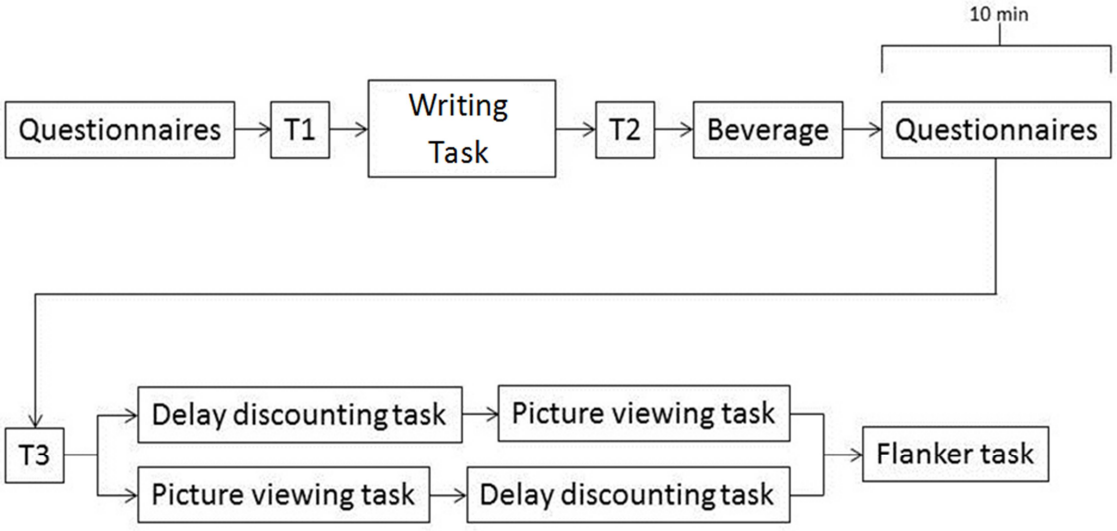


Figure 1.
Flow chart of the procedure. T1, T2, and T3 indicate time points of the blood glucose measurements.

Questionnaires. We assessed participants' demographic information and administered a collection of personality questionnaires to obscure the variable of

interest.[1] The measure of interest was the trait self-control scale (Tangney et al., 2004), which is a 13-item measure that asks participants to assess their capacity for self-control (e.g., "I am good at resisting temptation," $\alpha = .81$) using a 1 (*not at all like me*) to 5 (*very much like me*) scale. The mean score in the current sample was 32.51 ($SD = 7.46$).

Blood glucose. We took blood samples with Accu-Chek Safe-T-Pro single-use lancets (1.8 mm depth, 23 gauge/0.63 mm) and analyzed blood samples with an Accu-Chek Aviva blood glucose monitor. Participants were asked to rub their finger for a few seconds to facilitate blood flow, after which the experimenter cleaned the finger with an alcohol pad before using the lancet to prick the fingertip. The experimenter then applied pressure to get a blood sample, taking the third drop of blood to reduce contamination from the skin. The experimenter wore latex gloves (or non-latex in cases of allergies) while taking blood samples.

We assessed blood glucose prior to the writing task (T1), following the writing task (T2), and following a 10-minute questionnaire session after the beverage administration (T3). We obtained unstandardized residual values from regressions predicting T2 scores from T1 scores (to represent the change in blood glucose from the writing task) and predicting T3 scores from T2 scores (to represent the change in glucose from the beverage manipulation). Positive residual values indicated increases in blood glucose levels.

Writing task. After the first blood glucose measurement, participants were instructed to write a story on a blank sheet of paper for 6 minutes (see Schmeichel, 2007). Participants in the *free writing condition* were instructed to "Write a story about a

recent trip you have taken. It may be a trip to the store, Ohio, or another country – wherever! Please write until the experimenter asks you to stop." Those in the *controlled writing condition* received an additional instruction: "Very important! Please do not use the letters *a* or *n* anywhere in your story." Thus, one group was required to exercise self-control during the writing task but the other group was not. This manipulation has been used previously to induce ego depletion (e.g., Schmeichel, 2007). Immediately after the writing task the experimenter took a post-task blood glucose measurement as described above.

Beverage manipulation. After the second blood glucose measure, all participants were asked to sample a beverage that "may contain sugar or sweetener." The experimenter explained that the drink may contain sugar and that diabetics should not participate. Participants received either a glucose[2] or an aspartame solution. Those in the *glucose ingest condition* received 36g of sugar in a 400 mL solution (9% concentration) to consume. Participants in the *glucose swish condition* received 25 mL of the same solution to rinse their mouths with and then spit out after approximately 5 seconds. Those in the *aspartame condition* received a taste-matched aspartame solution (8g of aspartame in a 400 mL solution; 2% concentration) to consume.

Following the administration of the beverages participants answered a few questions regarding their experience of the solution. Specifically, they indicated whether they liked the beverage (yes or no), if they thought there was sweetener in it (yes or no), the approximate concentration of the sweetener (0-30%), and the type of sweetener used (sugar or Equal). Participants also completed personality questionnaires for 10 minutes

to allow any glucose to digest. Participants who completed the questionnaires before 10 minutes had elapsed were asked to wait quietly for the experimenter to set up the rest of the study (until the 10 minute mark). Those who took longer than 10 minutes were gently urged to complete their questionnaires. Another blood glucose measurement was taken following the questionnaires to check the success of the drink manipulation. Then participants either viewed pictures or completed a measure of future discounting in counterbalanced order.

Picture viewing. Participants passively viewed pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1990). Following a fixation cross presented for 3 s, positive, negative, and neutral pictures were presented for 3500-6000 ms with an ITI ranging from 2-12 s. They viewed 57 pictures presented in three blocks of 19. Approximately equal numbers of appetitive pictures (e.g., desserts, erotica) aversive pictures (e.g., attackers with weapons, injuries, predators, toilets) and neutral pictures (e.g., tools, buildings, neutral faces) were intermixed within each block. Participants viewed each picture for 6 seconds. Following each picture participants saw self-assessment manikin rating scales for valence and arousal that prompted them to rate how happy (valence) from 1 (*not happy*) to 7 (*happy*) and how calm or excited (arousal) from 1 (*calm*) to 7 (*excited*) the picture made them feel.

Future discounting task. Participants chose between pairs of hypothetical monetary rewards in 22 trials, split equally into two types. In the *delay trials* participants chose between $50 immediately versus other dollar amounts in three months, with values ranging from $50 to $100 in increments of $5. In the *acceleration trials*

participants chose between $75 in three months versus various dollar amounts immediately, from $75 to $25 in $5 increments. We assessed the indifference point as the value at which participants switched from taking the immediate reward to taking the greater, but delayed reward. For delay trials, higher values indicated that participants required more money to accept a 3 month delay, and thus higher values indicate greater discounting of future rewards. For acceleration trials, lower values indicate more discounting of the future, as participants would take even a small amount of money to avoid having to wait 3 months for a larger amount.

Flanker task. After the picture viewing and future discounting tasks, we administered a version of the flanker task (Eriksen & Eriksen, 1974) using left and right-facing arrows surrounded by groups of arrows facing the same direction (congruent trials; e.g., > > > > >) or the opposite direction (incongruent trials; e.g., > > < > >). Participants were instructed to quickly press a keyboard button indicating the direction of the middle arrow, ignoring the surrounding (flanking) arrows.

Trials began with the appearance of the surrounding arrows for 15 ms followed by the center arrow until the participant responded. Intertrial intervals ranged from 800 ms to 1100 ms, with 90% of the trials depicting congruent arrows and 10% of the trials depicting incongruent arrows. Following a practice session of 30 trials, participants completed 240 experimental trials in randomized order. After every 30 trials a reminder appeared on the screen prompting participants to be as fast and accurate as possible.

We scored flanker performance by calculating the percentage of correct responses to congruent, incongruent, and all trials (i.e., accuracy) as well as the average

reaction time overall and to each trial type (i.e., speed). We also calculated flanker interference scores by subtracting RTs to congruent trials from RTs to incongruent trials. In addition, we assessed post-error slowing by subtracting the average reaction time on correct trials immediately preceding an error from the average reaction time on trials immediately following an error, based on the recommendations of Dutilh et al. (2012). Greater difference scores represented more post-error slowing, such that participants responded more slowly after making a mistake. Individuals tend to slow down following an error, and this slowing pattern has been attributed to increased response caution (e.g., Dutilh et al., 2012) and good self-regulation (e.g., Robinson, Schmeichel, & Inzlicht, 2010). Thus, an increase in post-error slowing can be considered an indicator of good self-control.

Data analysis strategy

First we assessed the effect of the writing task on blood glucose levels immediately after the task to test the hypothesis that exercising self-control does not consume more blood glucose than a comparable task (Hypothesis 1). Next, we assessed the effects of the beverage manipulation on blood glucose levels measured 10 minutes after the beverage manipulation (Hypothesis 2). For our most crucial analyses we ran 2 (free vs. controlled writing) x 3 (glucose ingest, aspartame ingest, glucose swish) between-subjects ANOVAs on the primary dependent measures (Hypotheses 3-5). We also examined the correlations between blood glucose scores and our outcome measures to assess the relationship between both drink-induced blood glucose change (T2 to T3) and absolute blood glucose levels (T3) with the primary dependent measures

(Hypothesis 6). Lastly, we conducted exploratory analyses on the relationships among performance on the flanker task and the delay of gratification and emotional picture viewing measures.

We also took individual differences in self-control into account. People differ in their capacity for self-control, and individual differences in trait self-control have been found to predict performance on self-control tasks (e.g., Schmeichel & Zell, 2007). Therefore, we controlled for trait self-control in analyses when the outcome variable was correlated with trait self-control, so that we could ascertain the effects of our manipulations above and beyond the contributions of trait self-control.

CHAPTER VII

RESULTS

Blood glucose

First, we assessed the extent to which the writing manipulation influenced blood glucose levels. Six participants were excluded from analyses for having baseline or residual blood glucose scores > 3 *SD*s from the mean. Blood glucose dropped a small but statistically significant amount from baseline (T1; $M = 98.01$, $SD = 11.76$) to immediately following the writing task, (T2; $M = 96.64$, $SD = 11.52$), $t\ (146) = 2.07$, $p = .04$, $d = 0.12$. However, an ANOVA revealed no main effect of writing condition on glucose residuals (T1 to T2), $F\ (1, 145) = 0.40$, $p = .52$, $\eta_p^2 = .003$. Thus, consistent with Hypothesis 1, the controlled writing task did not cause larger drops in blood glucose compared to the free writing task.

Second, we verified that the drink manipulation influenced blood glucose levels (T2 to T3). A 2 (free writing vs. controlled writing) × 3 (glucose ingest, aspartame ingest, glucose swish) ANOVA revealed a main effect of drink condition, $F\ (2, 141) = 14.14$, $p < .001$, $\eta_p^2 = .17$. LSD post-hoc tests revealed higher residualized blood glucose values for those who ingested glucose ($M = 4.93$, $SD = 12.24$) compared to those who ingested aspartame ($M = 0.90$, $SD = 9.68$), $p = .05$, $d = 0.34$, who in turn showed a larger increase in blood glucose levels relative to those who swished glucose ($M = -5.88$, $SD = 7.68$), $p = .001$, $d = 0.78$.[3] Figure 2 displays the raw blood glucose values.

We also checked to see if participants could distinguish between the two

solutions. An ANOVA revealed a main effect of drink condition on participants' liking of the beverage, F (2, 145) = 4.49, p = .01, η_p^2 = .06. Post-hoc tests revealed that participants who ingested a beverage liked glucose (M = 1.53, SD = 0.50) and aspartame (M = 1.40, SD = 0.50) equally, p = .19. However, those who swished glucose liked the beverage (M = 1.69, SD = 0.47) more than those who drank aspartame, p = .003, d = 0.60. Swishing glucose was also rated as more likable than drinking glucose, though this effect failed to reach statistical significance, p = .10. There was no effect of drink condition on how confident participants were that sweetener was used, F (2, 145) = 0.02, p = .98, η_p^2 < .001, or the concentration of sweetener in the beverage, F (2, 145) = 0.34, p = .71, η_p^2 = .005. Finally, a chi-square test for independence revealed that participants were unable to identify the type of sweetener used regardless of which drink they received, X (2) = 3.88, p = .14.

We also examined whether the type of drink participants believed they had received influenced how their blood glucose levels changed as a result of consuming or swishing the drink. A 2 (expected glucose or expected aspartame) x 3 (glucose ingest, aspartame ingest, glucose swish) between-subjects ANOVA predicting glucose residuals (T2 to T3) found a main effect of drink condition, F (2, 135) = 13.64, p < .001, η_p^2= .168. The effect of expected drink was not significant, F (1, 135) = 0.66, p = .42, η_p^2= .005, nor was the Drink x Expected Drink interaction, F (2, 135) = 0.16, p = .85, η_p^2= .002. Thus, participants' beliefs about the solution they received did not influence their blood glucose levels.

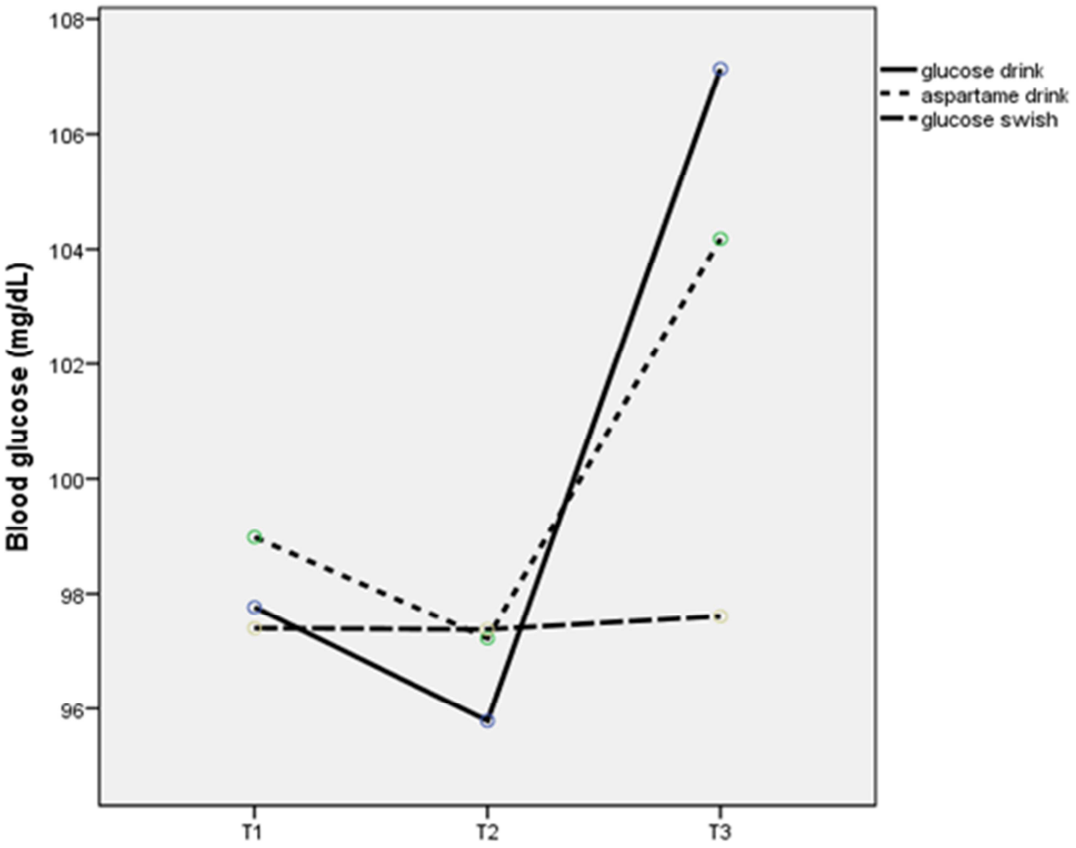


Figure 2.
Blood glucose levels from baseline (T1) to after the depletion task (T2) to 10 minutes following beverage administration (T3) by drink condition.

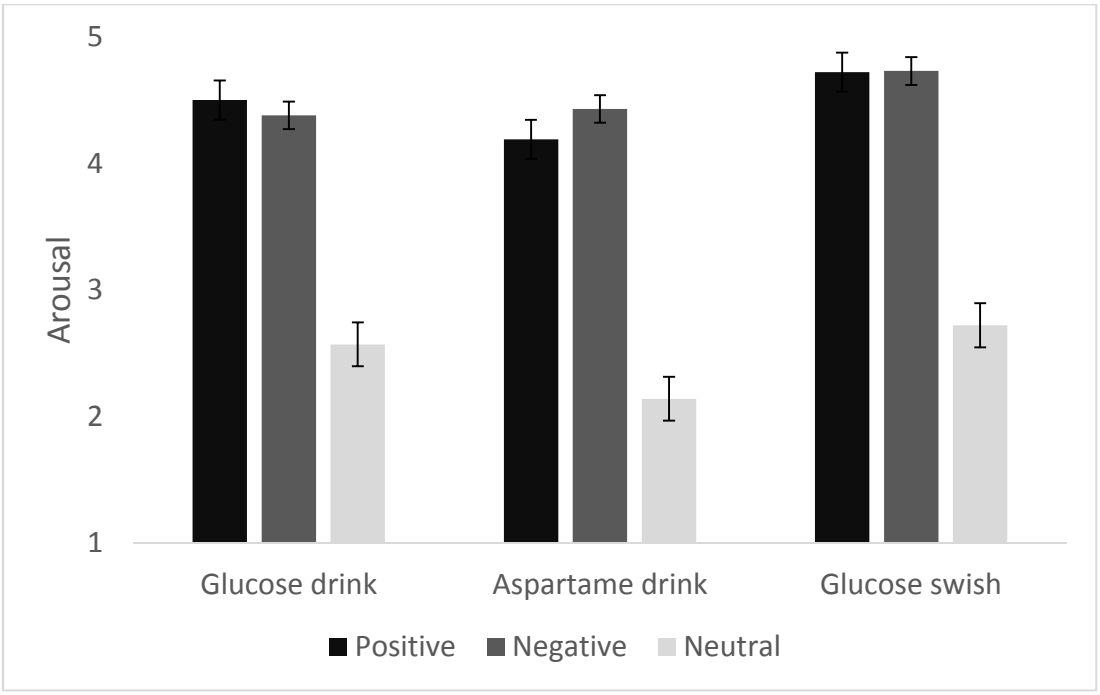
Picture viewing

As a manipulation check we examined the arousal and valence ratings for emotional versus neutral pictures. As expected, positive pictures induced more positive valence (M = 4.81, SD = 0.72) and negative pictures induced more negative valence (M = 2.08, SD = 0.65) compared to neutral pictures (M = 3.98, SD = 0.43), ts > 13.00, ps < .001, ds > 1.35. Furthermore, neutral pictures were rated as less arousing (M = 2.48, SD = 0.92) than both positive (M = 4.46, SD = 1.02) and negative (M = 4.51, SD = 1.08)

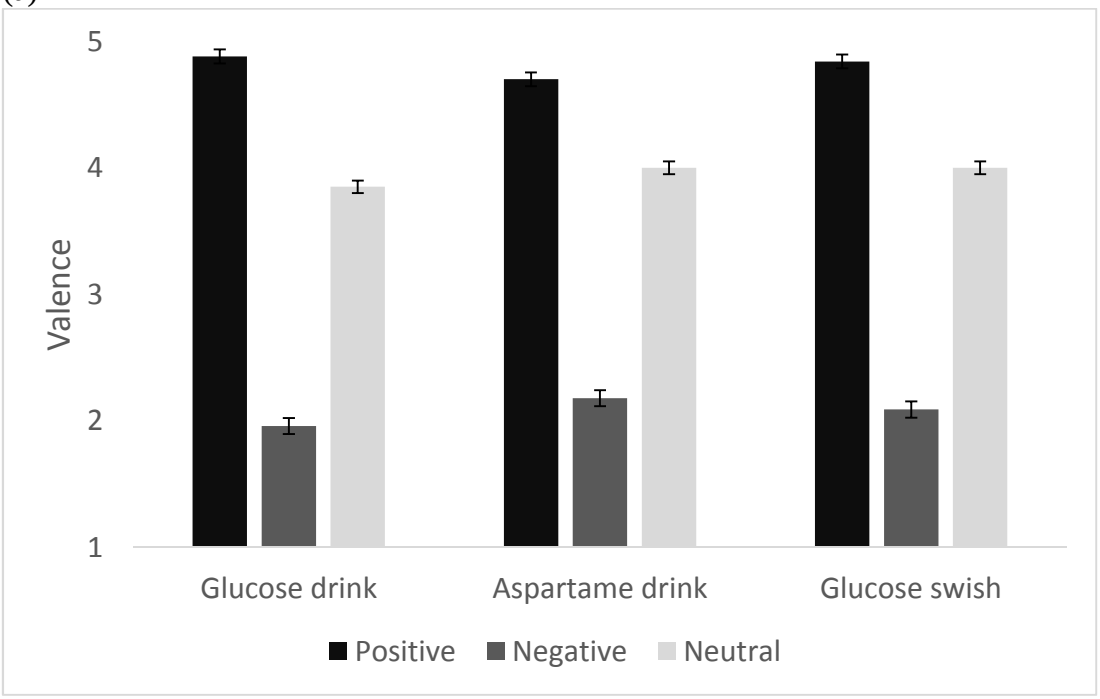
pictures, *t*s > 22.00, *p*s < .001, *d*s > 2.00. Arousal ratings did not differ between positive and negative pictures, t (151) = 0.53, p = .60, d = 0.05. Thus, the different picture types elicited the intended emotional responses.

Next, we assessed the effects of the drink and writing conditions on self-reported emotional reactivity to the pictures using a mixed ANOVA with drink condition and writing condition as between-subject predictors and the arousal ratings for positive, negative, and neutral pictures as within-subjects variables. Aside from the main effect of picture type on arousal (see above), F (1, 146) = 690.32, p < .001, η_p^2 = .83, we found no linear or quadratic interactions including picture type, drink condition, or writing condition, *F*s < 2.35, *p*s > .10, η_p^2s < .03. However, we did find a main effect of drink condition on arousal, F (1, 146) = 4.39, p = .01, η_p^2 = .06. Post-hoc tests revealed that those who swished glucose gave higher arousal ratings across picture types (M = 4.06, SD = 0.79) relative to those who ingested aspartame (M = 3.59, SD = 0.81), p = .004, d = 0.59. Arousal ratings among those who ingested glucose (M = 3.82, SD = 0.79) did not differ from the arousal ratings of participants in the other two conditions, *p*s > .13.

We repeated these analyses with the valence ratings for each picture type. No significant effects were found for any within-subjects interactions or between-subjects effects, *F*s < 1.80, *p*s > .17, η_p^2s < .03. See Figure 3.



(a)



(b)

Figure 3.
Arousal (a) and valence (b) ratings by condition and picture type.

Future discounting

We then examined the effects of the drink and writing conditions on future discounting rates. First, we calculated inverse discount scores for the acceleration trials, so that greater values indicated more discounting (to match the delay scores). Then we standardized the scores for both the delay and (inverted) acceleration trials. These two values were strongly correlated, r (148) = .70, $p < .001$, so we averaged them together to arrive at a discounting index. Higher values on the discounting index indicate increased discounting of the future (i.e., greater impulsiveness).

A 2 (free writing vs. controlled writing) × 3 (glucose ingest, aspartame ingest, glucose swish) ANOVA revealed no main effects of drink condition, F (2, 145) = 1.94, p = .15, η_p^2 = .03, writing condition, F (1, 145) = 0.51, p = .48, η_p^2 = .004, but the Drink × Writing interaction was significant, F (2, 145) = 3.46, p = .03, η_p^2 = .05.

To probe this interaction, we examined the effect of Drink separately by writing condition. The effect of Drink was not significant in the free writing condition, F (2, 78) = 0.13, p = .88, η_p^2 = .003, but there was a significant effect of Drink in the controlled writing condition, F (2, 67) = 4.94, p = .01, η_p^2 = .13. LSD post-hoc tests revealed that those who swished the glucose solution discounted the future less (M = 0.29, SD = 0.23) relative to those who ingested glucose (M = 0.54, SD = 0.33), p = .004, d = 0.88, or aspartame (M = 0.49, SD = 0.31), p = .02, d = 0.73.

Flanker task

Five participants were outliers (> 3 *SD*s from the mean) on the percentage of correct responses to congruent trials on the flanker task and thus were excluded from

flanker-related analyses. Within each participant, responses faster than 200 ms or slower than 800 ms were excluded from analyses. As expected, slower responses were correlated with higher accuracy, r (147) = .51, $p < .001$. Furthermore, accuracy was correlated with trait self-control, r (144) = .22, p = .01.We controlled for reaction times on correct trials and trait self-control in subsequent accuracy analyses.

Accuracy. First, we checked for accuracy effects by trial type with a 2 (free writing vs. controlled writing) × 3 (glucose ingest, aspartame ingest, glucose swish) × 2 (incongruent vs. congruent trial) mixed-model ANCOVA with reaction time and trait self-control as covariates. The Writing × Drink × Trial Type interaction was not significant, F (2, 136) = 1.23, p = .30, η_p^2 = .02, nor were any other interactions involving trial type, Fs < 0.60, ps > .40.

Next, we assessed overall accuracy via a 2 (free writing vs. controlled writing) × 3 (glucose ingest, aspartame ingest, glucose swish) ANCOVA with reaction time and trait self-control as covariates. We found a main effect of writing condition, F (1, 136) = 4.674, p = .032, η_p^2 = .03, such that those who were in the controlled writing condition performed more accurately (M = 92.61, SD = 3.79) than those in the free writing condition, (M = 91.07, SD = 4.74), d = 0.36. This effect was qualified by a significant Writing x Drink interaction, F (2, 136) = 3.68, p = .03, η_p^2 = .05. To probe this interaction we examined incongruent trial accuracy separately by writing condition. The drink manipulation did not influence the percentage of correct responses on incongruent trials in the free writing condition, F (2, 75) = 1.70, p = .19, η_p^2 = .04. In the controlled writing condition, however, the drink manipulation did influence accuracy on

incongruent trials, F (2, 59) = 4.66, p = .03, η_p^2 = .11. LSD post-hoc tests revealed that participants who swished glucose had higher accuracy (M = 93.75, SD = 3.21) compared to those who drank aspartame (M = 91.26, SD = 34.00), p = .01, d = 0.69. The glucose ingestion condition also showed higher accuracy (M = 92.60, SD = 2.54) versus the aspartame ingestion condition, though this difference fell just short of standard levels of statistical significance, p = .06, d = 0.40. The two glucose conditions did not differ, p = .46.

Overall, participants who had previously exercised self-control gave more correct responses on the flanker task if they received glucose solutions. Although the two glucose conditions showed similar patterns, swishing glucose appeared to be more effective at facilitating performance overall. See Table 1 in the Appendix.

Speed. We next assessed the extent to which the drink and writing manipulations influenced how quickly participants responded on the task, controlling for accuracy. We found no main effects of writing condition, F (1, 136) = 1.91, p = .17, η_p^2 = .014, or drink condition, F (2, 136) = 0.39, p = .68, η_p^2 = .006, on reaction times overall. The Writing × Drink condition interaction trended towards significance in predicting overall reaction times, F (2, 140) = 2.56, p = .08, η_p^2 = 0.04. Drink condition also did not influence the interference effect, F (2, 142) = 1.12, p = .33, η_p^2 = 0.02.

Post-error slowing. Controlling for trait self-control, post-error slowing correlated with the flanker accuracy, r (141) = .32, p < .001.Thus, consistent with previous research, slowing down after an error related to better performance.

We assessed the extent to which the experimental manipulations influenced post-error slowing. There were no main effects of drink condition, F (2, 141) = 0.55, p = .57, η_p^2 = .01, or writing condition, F (1, 141) = 0.27, p = .60, η_p^2 = .002, and no interaction, F (2, 141) = 1.02, p = .37, η_p^2 = .01. However, descriptively, participants who ingested (M = 46.16, SD = 30.62) or swished (M = 42.04, SD = 37.96) glucose more following errors than those who ingested aspartame (M = 39.37, SD = 30.80).

Correlations among tasks

Finally, we examined the relationships among performance on the flanker task, future discounting, and subjective responding to the picture viewing task, as well as their relation to blood glucose levels. The purpose of this analysis was to find possible connections among self-control performance and basic emotional or valuation processes. Given the exploratory nature of these analyses, results should be interpreted with caution.

Flanker accuracy correlated with valence ratings on neutral images, r (146) = .24, p = .004. This suggests that more positive reactions to neutral pictures related to better performance on the flanker task.

The percentage of incongruent trials participants answered correctly was negatively correlated with the discounting index, r (145) = .-.22, p = .008, such that the less individuals discounted the future, the better they later performed on the flanker task.

Baseline glucose levels did not relate to trait self-control, r (145) = .05, p = .59. Glucose residuals (T2-T3) and T3 scores also did not correlate with trait self-control, picture ratings, discounting rates, or flanker variables, rs < .12, ps > .15.

CHAPTER VIII

DISCUSSION

This study sought to replicate and extend previous research on glucose and self-control. We found no evidence that exercising self-control influenced blood glucose levels more than a similar non-self-control task. This result coincides with other null findings (e.g., Marcora et al., 2009; Molden et al., 2012) and casts additional doubt on the hypothesis that exercising self-control consumes inordinate amounts of blood glucose. Regarding the drink manipulation, swishing a glucose solution did not increase blood glucose levels whereas ingesting the same solution did. Ingesting aspartame also led to an increase in blood glucose levels relative to swishing glucose, but not to the same extent as glucose ingestion. Increases in glucose did not relate to our measures of future discounting, flanker performance, or emotional reactivity, nor did absolute blood glucose levels assessed 10 minutes after the drink manipulation. These results coincide with previous findings that the effects of glucose on self-control and control-related responding are not a matter of metabolizing glucose. We will next review our findings for each measure and examine the implications of the observed effects.

Emotional reactivity

We measured emotional reactivity to pictures to test the extent to which glucose influenced emotional responding. Specifically, we wanted to know if glucose would potentiate reward processes (i.e., reactions towards positive images) or influence negative affectivity. First, the writing manipulation did not influence emotional

reactivity. This was not particularly surprising insofar as participants had not been instructed to exercise self-control during the passive picture viewing task; thus, no ego depletion effect was expected. However, the drink manipulation did affect reactivity to the pictures. Specifically, participants reported the highest arousal levels regardless of picture type if they had swished glucose, followed by those who ingested glucose, followed by those who ingested aspartame. Valence ratings did not differ as a function of drink condition. These results may suggest that swishing glucose increases the subjective impact of emotional images. This conclusion is consistent with the suggestion that swishing glucose results in greater negative affect (Saunders & Inzlicht, in press), and also with the suggestion that glucose activates reward circuits (e.g., Hagger & Chatzisarantis, 2013). However, picture type did not factor in to the effect of drink condition on arousal. Thus, the observed increase in arousal was not driven by participants reacting more or less toward one type of image. Instead, those who swished the glucose drink reported greater arousal across all image types. This pattern suggests that swishing glucose caused a non-specific increase in arousal during the picture-viewing task, relative to consuming a glass of water laden with glucose or aspartame.

Our exploratory analyses revealed a connection between emotional responding to pictures and performance on the flanker task. Specifically, more positive ratings on neutral pictures were associated with better performance on the flanker task. Thus, whereas the drink manipulation influenced arousal ratings, valence seemed to be more related to self-control (as assessed by the flanker task).

Future discounting

We assessed future discounting to test the possibility that exerting self-control and then consuming or swishing glucose would influence the extent to which participants devalued future rewards. Although choosing a larger delayed reward over a smaller immediate reward is thought to require self-control, no studies to our knowledge have examined the effect of ego depletion on future discounting. However, discounting has been found to be influenced by glucose consumption (Wang & Dvorak, 2010). The current study yielded a null effect of prior exertions of self-control on future discounting. However, participants in the current study did exhibit reductions in future discounting rates after swishing, but not ingesting glucose. The beneficial effects of swishing glucose were not surprising, however we did not predict the null effects of glucose ingestion. This divergence in the effects of swishing versus ingesting glucose brings up the possibility of multiple and potentially antagonistic pathways towards influencing self-control.

Self-control

Lastly, we examined behavior on the flanker task, a measure requiring participants to focus on the direction of a central arrow and ignore distracting arrows. Given that performance on the flanker task requires focused attention and cognitive control, we expected to find that the writing manipulation of ego depletion would undermine flanker performance. We did not find evidence to support this prediction, but writing condition did interact with drink condition to influence flanker performance. More specifically, in the free writing condition, drink type did not influence flanker

performance, suggesting that the different drinks did not influence performance in the absence of previous self-control exertions. In the controlled writing condition, however, differences did emerge whereby both swishing and ingesting glucose improved performance relative to ingesting aspartame. Specifically, after performing the controlled writing task, swishing glucose led to fewer mistakes overall and to responding correctly on more incongruent trials. Among those who had performed the controlled writing task, participants in both glucose conditions outperformed participants in the aspartame condition. Ingesting glucose also increased post-error slowing to some degree, suggesting that participants who ingested glucose may have been more cautious after making errors.

Glucose thus appeared to increase either the motivation to use self-control or the capacity to exercise self-control on the flanker task, but only in the controlled writing condition. The lack of an effect of the drink manipulation in the free writing condition was somewhat unexpected given that previous studies have found beneficial effects of glucose on flanker performance among non-depleted persons (e.g., Brandt, et al., 2013). However, other studies have found beneficial effects of glucose administration only among participants who had previously exercised self-control (e.g., Molden et al., 2012), even when the previous exercise of self-control did not result in evidence of an ego depletion effect on task performance (e.g., Carter & McCollough, 2013). Likewise, in the current study we did not find that exercising self-control undermined flanker performance, but we did observe that glucose administration enhanced flanker performance among participants who had previously exercised self-control.

Glucose ingesting versus rinsing

The overall pattern of results points to beneficial effects of glucose over aspartame particularly among participants who had previously exercised self-control. The differences between swishing versus ingesting glucose were mixed. Swishing (versus ingesting) glucose led to increased arousal ratings for pictures and better performance on incongruent trials on the flanker task. Ingesting (versus swishing) glucose prompted more post-error slowing on the flanker task. These patterns do not clearly establish or rule out any contributions of non-oral glucose receptors in glucose effects.

CHAPTER IX

DISSERTATION STUDY II

In Study 1 study we found preliminary evidence that glucose influences performance on a cognitive control task (i.e., flanker task) and emotional reactivity to picture stimuli. However, these particular outcomes do not clearly point to underlying processes, which limits our ability to make conclusions about what mechanisms are driving the observed effects. We conducted another study to replicate the results from Study 1 and to help specify underlying processes of the observed glucose effects using EEG. To our knowledge, this study represents the first attempt to find neural effects of glucose administration under ego depletion.

CHAPTER X

METHOD

Participants

One hundred sixteen undergraduate students (43 men, 58 women, 15 unreported) participated in a laboratory experiment investigating the effects of sweeteners and sugar on cognitive ability and decision-making. They received credit toward a psychology course requirement for participating. All participants were asked to refrain from eating for 4 hours prior to the experiment to help ensure equivalent levels of blood glucose levels at the start of the experiment. Exclusion criteria included diabetes or other blood-related diseases. Seven additional students participated in the study but were excluded from analyses: two were excluded for reporting they had diabetes, two participants did not follow directions on the writing task, one participant reported they also participated in Study 1 in a prior semester, one participant was ill and did not complete the study, and one participant's condition was not recorded.

Procedure

We ran a follow-up study using nearly identical procedures as Study 1 and including EEG to measure brain activity. Because the most compelling effects from the initial study emerged in the controlled writing condition, the current study did not include a "non-depletion" condition. Fewer comparison conditions also provided the benefit of greater statistical power. Also, to account for potential order effects, we made slight modifications to the order of the tasks by changing the order in which the flanker

task was completed in relation to the other tasks. Namely, participants completed either the Flanker or picture viewing task in counterbalanced order before completing the future discounting task.

EEG recording and analyses. Participants were fitted with an EEG cap that recorded signals from 59 tin electrodes mounted on a stretch-lycra electrode cap (Electro-Cap International, Eaton, OH). Impedances were kept under 5000 Ω, and impedances at homologous sites were within 1000 Ω of each other. Signals were amplified (60-Hz notch filter), bandpass filtered (0.05–100 Hz) and digitized at 500 Hz. Signals were manually scored for artifacts before a regression-based eye movement correction was applied (Lindsley & Wicke, 1974). All epochs were extracted through a Hamming window.

Picture viewing task. The picture viewing task was similar to the picture viewing task used in Study 1. The same pictures were shown, and participants were asked to passively view the pictures. Instead of rating the pictures, we assessed the late positive potential (LPP) during picture viewing. The LPP is a waveform occurring after stimulus presentation and is sensitive to emotionally intense stimuli. Specifically, the LPP is greater following both pleasant and unpleasant (versus neutral) stimuli (Hajcak & Olvet, 2008; Schupp, Cuthbert, Bradley, Cacioppo, Ito, & Lang, 2000) and is thought to indicate emotional processing, as well as motivated and controlled attention (Hajcak, Dunning, & Foti, 2009). The data were epoched from 100 ms prior to 1000 ms following picture presentation, and low-pass filtered at 16 Hz (12 dB). The LPP was quantified as the maximum peak amplitude from the central electrode at which the LPP was largest

(Pz) in a time window from 500-1000 ms after stimulus onset. Amplitudes were averaged within positive, negative, and neutral trials. This measure provided a physiological index of emotional arousal to complement and extend the use of the self-report measure of arousal in Study 1.

Flanker task. The flanker task was similar to the flanker task used in Study 1. All of the stimuli and timing parameters were identical; the only difference was that participants completed 510 experimental trials instead of 240, in order to increase the likelihood of mistakes to assess neural indexes of error processing. We assessed the N2 and ERN on the flanker task. The N2 is a waveform following stimulus presentation that is thought to represent conflict monitoring and is greatest on high-conflict trials, such as the incongruent (versus congruent) trials on the flanker task. The data were epoched from 200 ms prior to 400 ms following stimulus presentation. We then applied a band-pass filter from 1-15 Hz (24 dB), and quantified the N2 as the minimum deflection 220-350 ms following stimulus presentation at the electrode with the greatest deflection amplitude (FCz).

The ERN is a negative deflection following an erroneous response. The data were epoched from 200 ms prior to 500 ms following participants' responses and band-pass filtered from 1-15 Hz (24 dB). The ERN was quantified as the minimum deflection 0-100 ms (ERN) after the response at electrode with the greatest deflection amplitude (FCz). Averages were computed within correct and incorrect responses.

Future discounting. Previous research has observed that glucose consumption can alter future discounting rates (Wang & Dvorak, 2010), and Study 1 found this effect

only for rinsing with a glucose beverage. We attempted to find an effect of glucose on future discounting again in the current study, but did not assess EEG during this task.

CHAPTER XI

RESULTS

Blood glucose

Blood glucose levels were measured at 3 time points: before the depletion task (T1), following the depletion task (T2), and 10 minutes following the administration of the drink (T3). Data from four participants were excluded for having blood glucose levels or fluctuations in blood glucose greater than 3 standard deviations away from the mean.

Descriptively, blood glucose levels dropped from T1 (M = 92.79, SD =10.70) to T2 (M = 90.95, SD =10.06), t (78) = 1.87, p = .07, d = 0.18, but this effect did not reach conventional levels of statistical significance. Next, we assessed the effect of drink condition on blood glucose changes from T2 to T3. We first obtained residual values from a regression predicting T3 blood glucose values from T2 values. Next, we ran a one-way ANOVA predicting residual blood glucose scores from drink condition. This effect was significant, F (2, 75) = 12.99, p < .001, η_p^2= .26. LSD post-hoc tests revealed a greater increase in blood glucose from ingesting both glucose (M =7.89, SD =18.41) and aspartame (M = 0.65, SD = 10.64), relative to the glucose swish condition (M = -10.95, SD = 7.57), ps < .005. Ingesting glucose resulted in a greater blood glucose increase than ingesting aspartame, , p = .05, d = .48. This pattern of changes in blood glucose levels closely mirrors the results from the pilot study, see Figure 4.

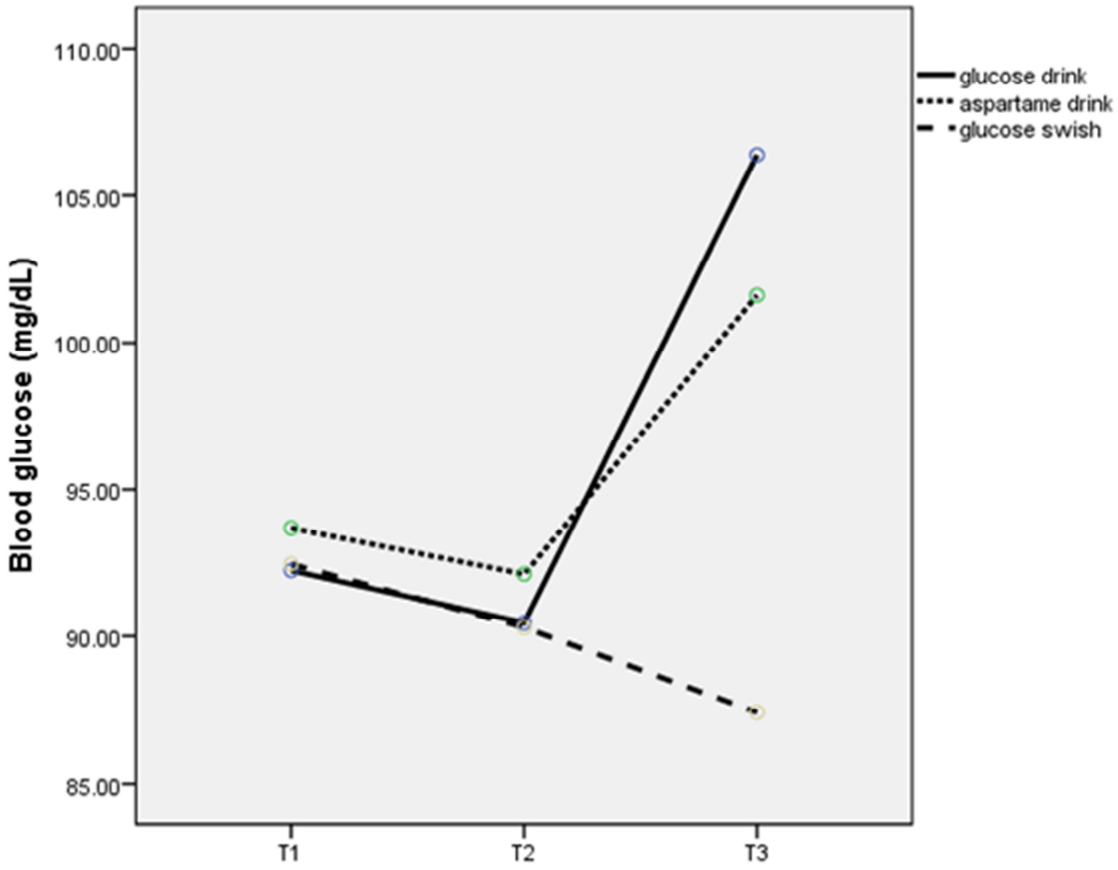


Figure 4.
Blood glucose levels from baseline (T1) to after the depletion task (T2) to 10 minutes following beverage administration (T3) by drink condition [Dissertation study II].

We also checked to see if participants could distinguish between the glucose and aspartame solutions. An ANOVA revealed a main effect of drink condition on participants' liking of the beverage, F (2, 99) = 5.16, p = .007, η_p^2 = .09. Post-hoc tests revealed that participants liked swishing glucose (M = 1.77, SD = 0.43) more than drinking aspartame (M = 1.40, SD = 0.50), p = .002. They also liked swishing glucose more than drinking an identical glucose solution (M = 1.61, SD = 0.49), p = .06, though this effect failed to reach conventional levels of statistical significance. The two ingest

conditions did not differ on participant liking, p = .17, suggesting equivalent liking for the glucose drink and the aspartame drink. There was no effect of drink condition on how confident participants were that sweetener was used, F (2, 100) = 0.43, p = .65, η_p^2 = .009, or how much sweetener participants believed was in the beverage, F (2, 100) = 0.92, p = .40, η_p^2 = .02. Finally, a chi-square test for independence revealed that participants were unable to identify the type of sweetener used regardless of which drink they received, X (2) = 0.02, p = .99.

We also examined whether the type of drink participants believed they had received influenced how their blood glucose levels changed as a result of consuming or swishing the drink. A 2 (expected glucose or expected aspartame) x 3 (glucose ingest, aspartame ingest, glucose swish) between-subjects ANOVA predicting glucose residuals (T2 toT3) found a main effect of drink condition, F (2, 66) = 11.51, p < .001, η_p^2= .26. The effect of expected drink was also significant, F (1, 66) = 1.93, p = .27, η_p^2= .03. Those who thought they received glucose showed a greater increase in blood glucose (M = 5.63, SD = 17.07) relative to those who thought they received aspartame (M = -2.56, SD = 13.39), t (70) = 2.26, p = .027, d = 0.53. The non-significant interaction term, F (2, 66) = 0.98, p = .38, η_p^2= .03, suggests that participants' beliefs about the solution they received influenced blood glucose levels regardless of which solution participants actually received.

Picture viewing task

Replicating a standard and robust pattern, the LPP was greatest following negative pictures (M = 13.88, SD = 7.11), followed by positive pictures (M = 11.60, SD

= 6.79), t (87) = 4.15, $p < .001$, d = 0.33, and LPP to positive pictures were likewise greater than those for neutral pictures (M = 5.75, SD = 6.24), t (87) = 10.80, $p < .001$, d = 0.90 (Figure 5).

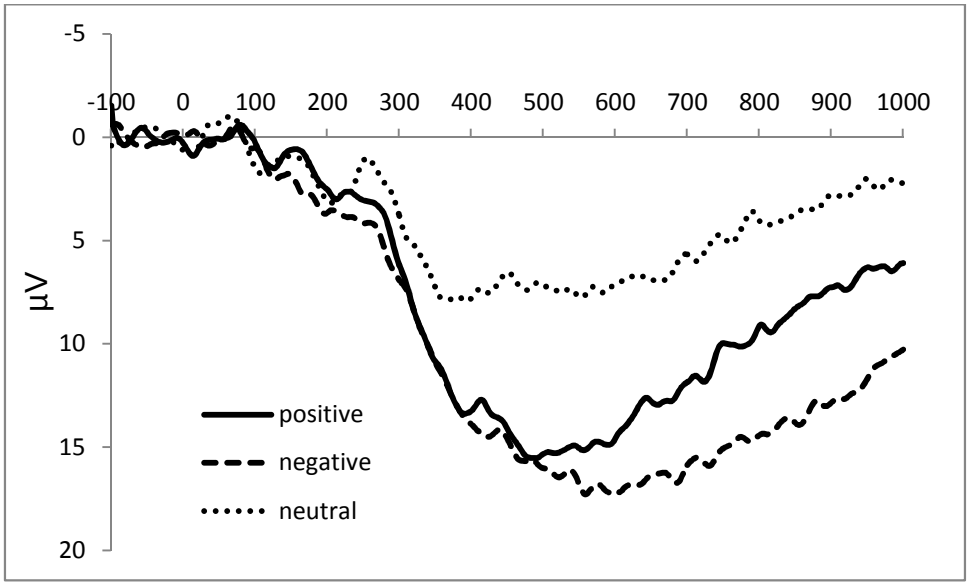


Figure 5.

Late positive potentials across condition. Epochs span from 100ms pre-stimulus to 1000ms after picture presentation.

We subtracted neutral LPP amplitudes from both positive and negative LPP scores, and submitted these difference scores to a MANOVA with drink condition as a predictor. Drink condition did not predict LPPs to either positive pictures, F (2, 85) = 1.04, p = .36, η_p^2= .24, or negative pictures, F (2, 85) = 2.50, p = .09, η_p^2= .06. As an exploratory analysis, we then combined the glucose conditions and ran the analysis again. This analysis yielded a significant effect, F (1, 86) = 4.44, p = .04, η_p^2= .05, such

that participants who received glucose had smaller LPPs to negative pictures (*M* = 7.44, *SD* = 4.959) relative to those who ingested aspartame (*M* = 9.59, *SD* = 3.09), *d* = 0.52, see Figure 6. Participants who received glucose also had smaller LPPs to positive pictures (*M* = 5.31, *SD* = 4.61) relative to those who ingested aspartame (*M* = 6.99, *SD* = 5.89), *d* = 0.32, but this effect failed to reach conventional levels of statistical significance, *F* (1, 86) = 2.10, *p* = .15, η_p^2= .02.

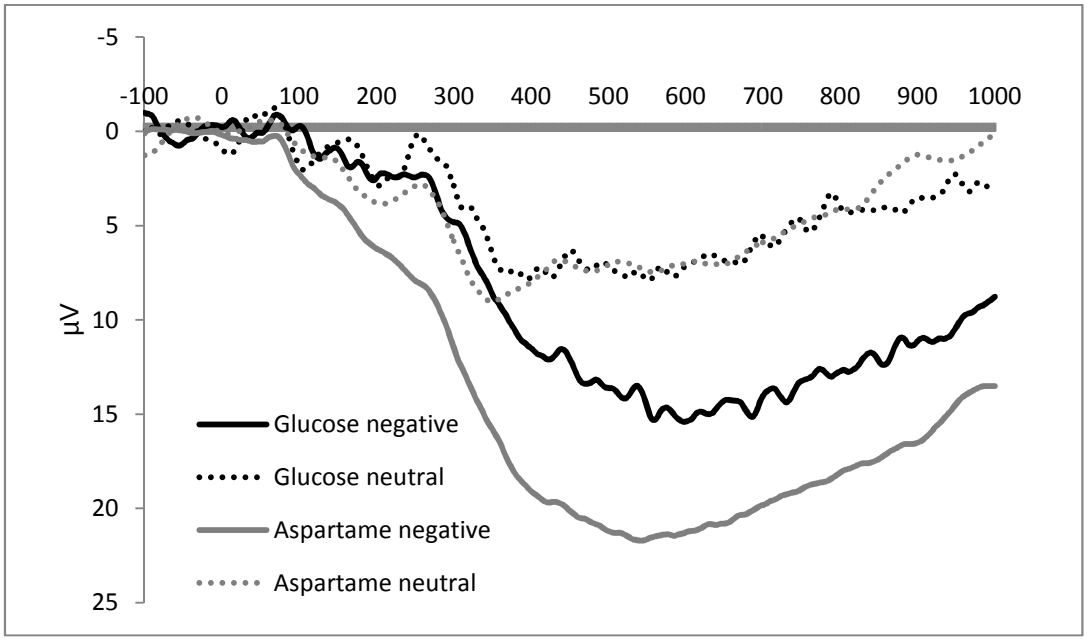


Figure 6.
Late positive potentials by condition. The glucose drink and glucose swish conditions were combined for this chart.

Flanker task

Eleven participants were outliers (> 3 *SD*s from the mean) on the percentage of correct responses to congruent trials on the flanker task or the number of trials they did not respond to and thus were excluded from flanker-related analyses. Within each participant, responses faster than 200 ms or slower than 800 ms were excluded from analyses. As expected, slower responses were correlated with higher accuracy, r (91) = .24, p = .02.

Accuracy. We assessed overall flanker accuracy as well as accuracy on incongruent and congruent trials separately using an ANCOVA including reaction times on correct trials as a covariate. Drink condition did not predict overall accuracy, F (2, 87) = 0.29, p = .75, η_p^2 = .007, accuracy on incongruent trials, F (2, 87) = 0.02, p = .98, η_p^2 = .001, or accuracy on congruent trials, F (2, 87) = 0.57, p = .57, η_p^2 = .013.

Speed. Participants responded more slowly on incongruent trials (M = 461.54, SD = 63.15) versus congruent trials (M = 316.83, SD = 44.09), t (90) = 29.11, p < .001, d = 0.82, showing the classic interference effect. This effect was not influenced by drink condition, F (2, 88) = 0.28, p = .75, η_p^2 = .006.

We next assessed the extent to which the drink manipulation influenced how quickly participants responded on the task, controlling for accuracy. We found no effect of drink condition on response times overall, F (2, 87) = 0.48, p = .62, η_p^2 = .01, on incongruent trials, F (2, 87) = 0.006, p = .99, η_p^2 < .001, or on congruent trials, F (2, 88) = 0.33, p = .72, η_p^2 = .008.

Post-error slowing. Post-error slowing (i.e., the average RT increase on trials immediately following an error) correlated with the percentage of correct responses on incongruent trials, r (91) = .22, p = .04, as well as with overall accuracy, r (91) = .23, p = .03. Thus, consistent with previous research, slowing down after an error was related to better accuracy. Drink condition did not influence post-error slowing, F (2, 87) = 0.22, p = .81, η_p^2 = .005.

Neural indexes

We examined neural responses indicating conflict monitoring prior to button presses (N2) as well as neural indicators of error detection and action monitoring following error commission (ERN). We averaged peak values for correct and incorrect trials within each participant. We confirmed that N2 values on correct incongruent trials (M = -5.02, SD =4.92) were greater (more negative) than those for correct congruent trials (M = 0.20, SD = 3.03), t (76) = 9.50, p < .001, d = 1.28 (Figure 7). ERN scores on incorrect trials (M = -3.90, SD = 5.09) also showed a greater deflection than those for correct trials (M = 0.11, SD = 2.82), t (74) = 7.17 p < .001, d = 0.98, as expected (Figure 8).

N2. We calculated difference scores for N2 average peak values by subtracting values for correct incongruent trials from those of correct congruent trials. Thus, greater values indicate a greater N2 for incongruent versus congruent trials. Greater N2 amplitudes (congruent minus incongruent) predicted greater accuracy, r (76) = .26, p = .02, but were not related to reaction times nor to post-error slowing, rs < .20, ps > .09. Drink condition did not predict N2 amplitudes, F (2, 74) = 0.84, p = .43, η_p^2 = .02.

Descriptively, those who ingested glucose showed the greatest N2s (*M* = 4.07, *SD* = 4.79), followed by the glucose swish condition (*M* = 3.07, *SD* = 4.52), followed by the aspartame ingest condition (*M* = 2.39, *SD* = 4.89).

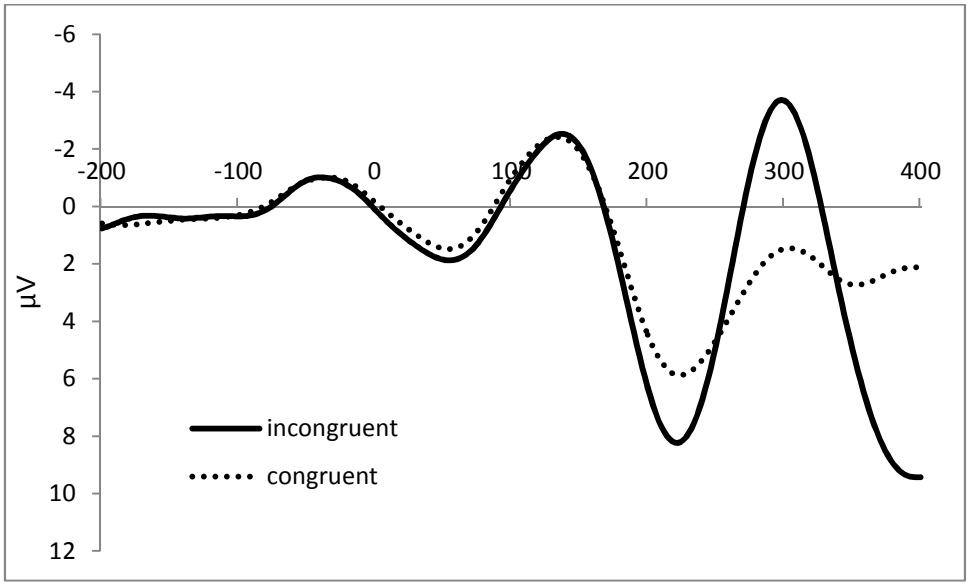


Figure 7.
N2 peaks across condition. Epochs span from 200ms pre-stimulus to 400ms after picture presentation.

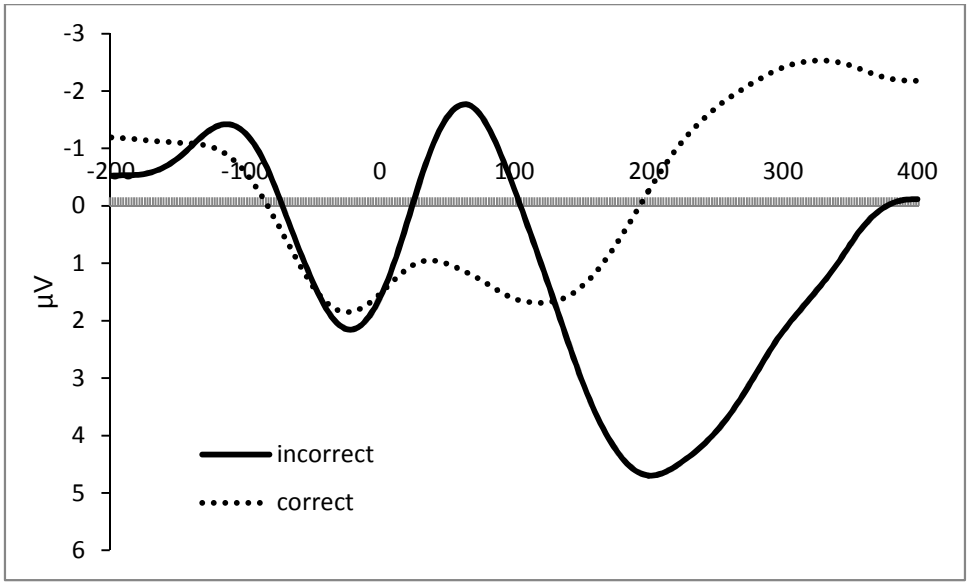


Figure 8.

Error-related negativity across condition. Epochs spanned from 200ms pre-response to 400ms after button press.

ERN. We calculated ERN difference scores then by ERN values on incorrect trials from correct trials. Thus, greater values indicate a greater ERN for incorrect versus correct trials. Greater ERN difference scores predicted greater accuracy, r (74) = .43, p < .001, but were not related to reaction times nor to post-error slowing, rs < .20, ps > .10. Drink condition did not predict ERN amplitudes, F (2, 72) = 0.42, p = .66, η_p^2 = .01. Descriptively, those who ingested glucose showed the greatest ERNs (M = 2.89, SD = 4.46), followed by the aspartame ingest condition (M = 2.24, SD = 5.18), followed by the glucose swish condition (M = 1.76, SD = 3.55).

Given that both pre-action (N2) and post-error (ERN) neural indexes were related to accuracy on the flanker task, it is perhaps not surprising that N2s and ERNs were also positively correlated, r (74) = .25, p =.03.

ERNs were correlated with glucose residuals (T2 toT3), r (56) = .32, p = .02, as well as with raw blood glucose levels at T3 (following the drink), r (56) = .39, p =.003. We found no such relationship between blood glucose and N2s, rs < .12, ps > .35. Thus, blood glucose levels were related to post-error action monitoring rather than conflict monitoring before each response. Controlling for blood glucose residuals did not influence the null effect of drink condition on ERNs, F (2, 52) = .47, p = .63, η_p^2= .02.

Future discounting

We then examined the effect of drink condition on future discounting rates. First, we calculated inverse discount scores for the acceleration trials, so that greater values indicated more discounting (to match the delay scores). Then we standardized the scores for both the delay and (inverted) acceleration trials. These two values were highly correlated, r (95) = .51, p < .001, so we averaged them together to arrive at a discounting index. Higher values on the discounting index indicate increased discounting of the future (i.e., greater impulsiveness).

A one-way ANOVA revealed no significant effect of drink condition, F (2, 92) = 1.44, p = .24, η_p^2 = .03. However, the pattern of means closely matched those of Study 1, such that those who swished glucose showed reduced future discounting (M = 0.37, SD = 0.29) versus those who ingested glucose (M = 0.48, SD = 0.29) or aspartame (M = 0.49, SD = 0.27).

Correlations among tasks

One of the goals of this study was to explore plausible mechanisms by which glucose may influence self-control. To do this, we looked for relationships between various aspects of flanker performance and emotional or reward-related decision making processes. We also assessed the possible effects of glucose on these processes.

Emotional processes. Flanker accuracy was related to LPP amplitude for positive, r (74) = -.25, p = .03, neutral, r (74) = -.30, p = .009, and negative images, r (74) = -.29, p = .01. Thus, accuracy on the flanker task appeared to be tied to general affective processing, such that those who were more accurate showed less emotional reactivity.

Future discounting. Although future discounting was not significantly reduced by glucose, lower discounting factors were nevertheless related to better accuracy on congruent trials of the flanker task, r (79) = -.24, p = .03. Thus, participants who were more accurate on the flanker task discounted the future less.

Blood glucose. Blood glucose levels at T3 or the residual from T2 to T3 was not correlated with flanker accuracy or speed, rs < .10, ps > .40, nor LPPs towards any picture type, rs < .12, ps > .30, and there was no relationship between blood glucose levels and future discounting, r (61) = -.04, p = .75. However, individuals tended to show larger ERNs if they had greater levels of glucose at T3, r (56) = .39, p = .003, as well as greater residuals from T2 to T3, r (56) = .315, p = .018. As blood glucose increased in both the glucose and aspartame ingest conditions, we examined the correlations within each drink condition. Only the glucose ingest condition showed

correlations between ERN amplitudes and glucose at T3, r (21) =.40, p = .08, or glucose residuals, r (21) = .38, p = .09, though these correlations fell just short of statistical significance. Correlations between blood glucose and ERNs were not significant in either the aspartame or glucose swish conditions, rs ranged from -.05 to .27, ps > .25.

CHAPTER XII

GENERAL DISCUSSION

Across both studies we found no evidence that exercising self-control consumes blood glucose. As expected, ingesting a glucose solution led to an increase in blood glucose levels. As in Study 1, this increase was matched by a comparable increase in blood glucose among those who ingested aspartame, and no change among those who only swished a glucose solution.

Emotional reactivity

We asked participants to passively view emotional images and assessed their neural responses to the images, as indexed by the LPP. Relative to the aspartame condition, those who received glucose showed reduced reactivity toward emotional stimuli, especially aversive pictures.

This pattern contrasts with the results of Study 1, wherein swishing glucose led to increased self-reported arousal toward all stimuli. We did not ask participants to self-report their arousal in Study 2, so it is unclear whether the two studies found opposite effects, or whether glucose decreased emotional processing at the neural level but increased subjective emotional arousal. Assuming glucose produced divergent emotional reactions at the neural and subjective level, this would suggest that glucose reverses the effects of depletion on emotion found by Wagner and Heatherton (2013), who observed that exerting self-control increases emotional reactivity at the neural level.

Future discounting

Study 1 revealed that rinsing with a glucose beverage reduced future discounting rates. Further, discounting rates were related to self-control performance on the Flanker task. In Study 2, we observed no effects of glucose on future discounting, though the pattern of means closely matched those of Study 1. The null effects of glucose ingestion observed in the present studies contradict published evidence that glucose reduces delay discounting (Wang & Dvorak, 2009). Many differences in methodology exist that may explain the inconsistent findings. For example, Wang and Dvorak did not deplete participants prior to administering glucose, and the version of future discounting they used included larger amounts of money in addition to the chance that participants would obtain one of their choices. By contrast, in the current study all participants completed a self-control task in the first phase of the study, and the future discounting measure included only hypothetical rewards.

Self-control

Lastly, we examined both behavioral measures of self-control (performance accuracy, speed, and post-error slowing) as well as neural indexes of conflict and action monitoring (N2, ERN) on the flanker task. Unlike Study 1, trait self-control did not predict performance in Study 2, nor did the drink manipulation, though the pattern of means was in the predicted direction. As the sample was smaller in Study 2 than in Study 1, we lacked the necessary statistical power to detect the former effects. Further, we did not find an effect of drink condition on the neural measures, though again the

pattern of means was in the predicted direction (i.e., glucose increasing neural indicators of conflict and action monitoring).

Glucose ingesting versus rinsing

Both studies found comparable effects of swishing and ingesting glucose on self-control performance, as well as on emotional and reward-related tasks. Study 1 found greater benefits of swishing glucose versus consuming either aspartame or glucose on flanker accuracy without compromising speed, whereas Study 2 found a potential pathway of ego replenishment through blood-glucose-inflated ERNs. At this stage, these patterns do not clearly establish or rule out any contributions of non-oral glucose receptors in glucose effects.

Mechanisms of self-control

Glucose as a resource. Blood glucose levels and fluctuations did not relate to emotional reactivity, future discounting, or self-control in Study 1 or Study 2. However, in Study 2, post-drink blood glucose (T3) and the increase in blood glucose from T2-T3 were both related to increased ERNs. This correlation suggests that circulating levels of glucose in the bloodstream are related to the magnitude of error-related neural activity. This implication is consistent with the idea that glucose can enhance self-control, insofar as the ERN reflects control-related processes.

Control through emotional processes. Various theories suggest possible influences of reward-related positive affect, conflict-related negative affect, or emotions in general on self-control performance. Our exploratory analyses from Study 1 suggested greater subjective positivity toward neutral images may be related to self-control

performance. Study 2 yielded a different pattern, such that lower emotional reactivity toward all picture types was related to better self-control. Neither the self-report results from Study 1 nor the neural indexes of emotional reactivity from Study 2 provide clear support for the idea that negative affect in particular (i.e., related to conflict) is enhanced by the glucose manipulation, which may in turn facilitate cognitive control (Saunders & Inzlicht, in press). Further studies are needed including both subjective and neural measures to clarify the implications of the current mixed pattern of results.

Discounting of future reward. The finding that discounting of future rewards was related to accuracy on incongruent (Study 1) and congruent (Study 2) trials of the Flanker task reinforces theoretical connections between future discounting and reflexive measures of self-control. However, we found that only rinsing glucose appeared to reduce future discounting following ego depletion, and future studies should probe this effect further to address the potential pathways by which glucose influences self-control.

Limitations

Given the inconsistencies in results between the two studies and the exploratory nature of some of the significant effects, the current results should be interpreted with care. Our study design would benefit from a larger sample size to accommodate the number of comparison conditions; effects that were significant only in Study 1 may have been too small to detect in Study 2. Indeed, a power analysis revealed that in order to obtain the main effect of drink condition on flanker variables and future discounting we found in Study 1 with a medium effect size and a power of 0.80, we would have required a sample greater than 150 participants in Study 2. In this light, it is perhaps not

surprising that we did not find a significant main effect of drink on self-control or future discounting in Study 2.

Regarding the flanker task, although it is purported to tap into control processes, it is an uncommonly used task in the ego depletion literature. Furthermore, flanker performance may only represent a portion of what is commonly defined as self-control. Specifically, the flanker task evaluates how quickly one can quash the tendency to respond in a way that is 1) primed by global stimuli and 2) habitual due to the high proportion of congruent trials. While performance on the flanker task may reflect success at inhibitory control, it lacks the motivated and sustained control that is characteristic of tasks measuring persistence (e.g., impossible puzzle or anagram tasks) and other more ecologically valid measures (e.g., choosing healthy versus unhealthy food) of self-control. The current study may only apply toward a portion of the umbrella construct referred to as self-control.

CHAPTER XIII

CONCLUSIONS

The current studies attempted to provide evidence for mechanisms behind the restoration of self-control following self-control exertion. We approached this endeavor from two angles. First, we included both a glucose ingest and a glucose swish condition, as no prior studies have directly compared the effects of the two manipulations on self-control. Overall, we found evidence for the effectiveness of both consuming and rinsing the mouth with glucose, although they may facilitate self-control through different mechanisms. Second, we invited participants to complete tasks delving into potential emotional and reward-related processing, and collected neurophysiological data to complement the behavioral and subjective results common in the literature. This data suggested that in addition to processes related to monitoring of actions, glucose may also influence self-control through emotional processes. The resulting patterns are complex, but provide a crucial step in examining the processes that may influence self-control.

NOTES

[1] We included other questionnaires assessing constructs that may be related to self-control. These included the behavioral inhibition and behavioral activation scales (BIS/BAS; Carver & White, 1994), approach-avoidance temperament questionnaire (Elliot & Thrash, 2002), a handedness questionnaire, the PANAS-X, (Watson & Clark, 1994), the Barratt impulsiveness scale (Barratt, 1959), and the Berkeley expressivity questionnaire (BEQ, Gross & John, 1995). Data pertaining to these scales are available upon request.

[2] We created the solutions using table sugar (sucrose), which is digested by the small intestine into glucose and fructose. We refer to our solution as "glucose" in keeping with the literature.

[3] An increase in blood-glucose resulting from aspartame ingestion has been observed in other studies. Such an increase has been attributed to individual differences in insulin responses due to the sweetness of the drink, despite the lack of carbohydrates (e.g., Melanson, Westerterp-Plantenga, Campfield, & Saris, 1999), although this explanation is in doubt. Some theorists have suggested that aspartame ingestion produces a sort of "caloric crisis" in which the body expects nutrients and receives none (Swithers, 2013). Further, increases in blood glucose following aspartame ingestion could be influenced by individual differences in artificial sweetener consumption.

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APPENDIX

Table 1.

Flanker performance as a function of experimental condition.

	Controlled writing				Free writing			
	Incongruent		Congruent		Incongruent		Congruent	
	M	SD	M	SD	M	SD	M	SD
Accuracy (% correct)								
glucose drink	60.42_a	14.19	97.88_b	1.35	61.79_a	20.79	96.69_a	3.10
aspartame drink	59.15_a	17.94	96.22_a	3.35	60.96_a	23.16	96.75_a	3.85
glucose swish	70.48_b	11.23	98.27_b	1.52	57.16_a	18.68	95.15_a	4.30
Reaction times (ms)								
glucose drink	431.26_a	49.60	291.05_a	32.67	450.63_a	46.63	311.43_a	32.34
aspartame drink	450.34_a	58.14	307.42_a	38.35	434.47_a	58.06	295.60_a	36.32
glucose swish	441.17_a	38.62	297.39_a	28.65	419.69_a	62.00	299.49_a	37.66

Note. Means within columns with different subscripts differ at $p < .05$.