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Abstract

According to the resource-depletion model, self-control is a limited resource that is depleted after a period of exertion. Evidence consistent with this model indicates that self-control relies on glucose metabolism and glucose supplementation to depleted individuals replenishes self-control resources. In five experiments we tested an alternative hypothesis that glucose in the oral cavity counteracts the deleterious effects of self-control depletion. We predicted a glucose mouth rinse, as opposed to an artificially-sweetened placebo rinse, would lead to better self-control after depletion. In Studies 1-3 participants engaging in a depleting task performed significantly better on a subsequent self-control task after receiving a glucose mouth rinse, as opposed to participants rinsing with a placebo. Studies 4 and 5 replicated these findings and demonstrated that the glucose mouth rinse had no effect on self-control in non-depleted participants. Results are consistent with neural rather than metabolic mechanism for the effect of glucose supplementation on self-control.

Key words: self-regulation, motivation and performance, strength model, oral glucose sensing, sugar mouth rinse, dual-task procedure

The Sweet Taste of Success: The Presence of Glucose in the Oral Cavity Moderates the Depletion of Self-Control Resources

Control over the self is an adaptive human trait. People demonstrate considerable capacity to overcome biologically-driven urges and impulses, and forego immediate gratification, in pursuit of long-term goals (Metcalfe & Mischel, 1999). ‘Good’ self-control has been shown to be associated with success in school and the workplace, better health, harmonious social and romantic relationships, and optimal psychological well-being and quality of life (Tangney, Baumeister, & Boone, 2004). Conversely, regular lapses in self-control are associated with increased susceptibility to drug addiction, criminality, alcoholism, obesity, chronic illness, and compulsive gambling (Cervone, 1996). These findings have led to a proliferation of research in social psychology aiming to identify the correlates of ‘good’ self-control and develop theoretical models to explain the processes and mechanisms that underlie self-control.

One prominent approach conceptualizes self-control as a limited resource that enables people to override impulses, break habits, and change ingrained, well-learned patterns of action (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Muraven, Tice, & Baumeister, 1998). Self-control, therefore, reflects the extent to which an individual can overcome a dominant behavioral response in favor of some alternative course of action. As the resource is finite, self-control resources are hypothesized to become depleted after period of exertion leading to decreased self-control capacity. Resources can only be restored after a period of rest or recovery. The state of diminished self-control resources has been termed ‘ego-depletion’ (Baumeister et al., 1998). Experimental tests of the limited-resource model have tended to adopt a dual-task paradigm in which participants are randomly assigned to receive an initial task that requires self-control or a task that does not require self-control (see Appendix A). Participants subsequently engage in a second self-control task, performance on which constitutes the dependent measure of self-control. The extent to which performance on the second task is impaired in participants receiving an initial task that required self-control, relative to those receiving a first task did not require self-control, provides confirmation of the ego-depletion effect. This intuitively-appealing model has been supported by a large volume of research in diverse domains of self-control such as emotional and thought regulation, impulse control, interpersonal relationships, and financial management (Hagger, Wood, Stiff, & Chatzisarantis, 2010). Despite impressive confirmatory evidence for the model, the mechanisms responsible for its predictions remain elusive (Hagger et al., 2010).

Foremost among the outstanding questions for the resource-depletion model is exactly what it is that becomes ‘depleted’ and how it exerts its effects on people’s capacity to control their impulses and temptations. Following Baumeister et al.’s (1998) original assertion that it is “implausible that ego depletion would have no physiological aspect or correlates at all” (p. 1263), researchers have suggested that self-control resource depletion may be linked to the metabolism of glucose in the brain (Gailliot et al., 2007). To support their hypotheses, Gailliot et al. found that depletion was associated with drops in blood glucose while oral supplementation of glucose enhanced self-control. They suggested that glucose ingestion promoted better self-control through the supply of more fuel to the brain and may be a candidate physiological analog for the ego-depletion effect (Gailliot et al., 2007).

The purpose of the present investigation is to test an alternative explanation to the one provided by Gailliot et al. (2007) for the role of glucose supplementation in promoting better self-control. Specifically, we hypothesize that the moderating effect of oral glucose supplementation on self-control resource depletion is a centrally-mediated effect in which the sensing of glucose in the mouth stimulates increased self-control. The proposed effect follows on from research in exercise physiology that has found the presence of glucose in the oral cavity increases athletes’ physical performance on endurance time trials independent of supply and availability (Carter, Jeukendrup, & Jones, 2004; Chambers, Bridge, & Jones, 2009). An explanation for this effect has been derived from behavioral neuroscience research demonstrating that oral receptors sensitive to glucose activate brain regions associated with reward, motivation, and motor control (Chambers et al., 2009). It is possible, therefore, that the enhancement of self-control in depleted individuals receiving an oral glucose supplement is attributable to increased neural activity in these brain regions rather than the metabolism of glucose. We will investigate this unique hypothesis by adopting the novel ‘mouth rinse’ procedure used in physiology research (Carter et al., 2004).

Self-Control and Glucose Supplementation

In search of physiological correlates for the self-control resource depletion effect, Gailliot et al. (2007) proposed that self-control tasks are unique in that they demand more energy and should, therefore, consume more fuel in the brain, than other tasks. They proposed that the high energy cost of self-control processes is likely to be indicated by increases in glucose metabolism, the primary metabolic fuel for brain function, when individuals engage in tasks requiring self-control. They cited evidence from psychophysiology that adequate cognitive functioning relies on adequate supply and availability of glucose in the brain as a basis for their hypothesis (e.g., Benton, Parker, & Donohoe, 1996). Initial tests supported their proposals revealing that engaging in self-control tasks coincided with drops in blood glucose. In addition, they also found that ingesting a glucose solution replenished self-control capacity (Gailliot et al., 2007), a finding that has been subsequently replicated in numerous studies (e.g., DeWall, Baumeister, Gailliot, & Maner, 2008; Dvorak & Simons, 2009; Masicampo & Baumeister, 2008). Gailliot et al. (2007) suggested that the mechanism by which glucose supplementation enhances self-control is through increased supply of glucose to the brain to provide additional fuel for the costly self-control tasks.

While Gailliot et al.’s (2007) work on glucose provides a preliminary indication of what is depleted in ego-depletion experiments, the findings have been challenged. In a review of Gailliot et al.’s work, Kurzban (2010) argued that that the role of glucose as a mediator of self-regulatory resource depletion was overstated. His critique was based on literature indicating that although engaging in self-control tasks probably consumes more glucose than other cognitive processes, the amount of glucose consumed by the brain in performing such tasks is negligible. He argued that variations in glucose availability and supply to the brain are unlikely to be a problem for self-control as the absolute energy cost of such tasks is minimal. Similarly, Beedie and Lane (2011) contend that the body is able to supply glucose to the brain rapidly and effectively, even at times when availability is limited, making drops in brain glucose a less likely candidate as a mediator of self-control resource depletion. We also note that no research to date has directly measured glucose consumption in the brain to validate the supplementation effects found in other studies (Heatherton & Wagner, 2011).

Metabolic vs. Central Explanations for the Effect of Glucose Supplementation

In light of the critique of the metabolic explanation for the moderating effect of glucose supplementation on self-control resource depletion, it may be fruitful to search for alternative explanations. One possible line of research that may contribute to this understanding comes from studies examining the effect of glucose on exercise performance in the fields of exercise physiology and behavioral neuroscience. Researchers in these fields noted that athletes’ performance in endurance cycling and running time trials was improved as a result of ingesting a glucose or carbohydrate solution, even though there was ample intrinsic fuel available in the muscles for the duration of the exercise task. In subsequent studies, researchers found that rinsing the mouth with a glucose or carbohydrate solution, without ingestion, resulted in similar facilitative effects compared to placebo solutions containing artificial sweetener (Carter et al., 2004; Chambers et al., 2009).

It was proposed that a central (perceptual responses in the brain) rather than metabolic (metabolism of glucose in the brain) process may be responsible for the effect. Oral receptors sensitive to sugars like glucose were not only proposed to signal increased activation in taste-specific regions in the brain but also in regions associated with reward, motivation, and motor control (Chambers et al., 2009; Jeukendrup & Chambers, 2010). This was confirmed in a neuroimaging study that showed increased activity in these brain regions in response to the presence of glucose in the oral cavity but not to an artificially-sweetened placebo (Chambers et al., 2009). Specifically, Chambers et al.'s imaging data indicated that sensing oral glucose stimulated activity in the anterior cingulate cortex (ACC) and the ventral striatum brain regions. Introducing saccharin, an artificial sweetener, into the mouth did not induce activation in these regions consistent with research indicating that separate taste receptors sensitive to sugars (e.g., glucose) and sweetness may be present in the oral cavity (Damak et al., 2003). These brain regions are proposed to mediate behavioral responses to rewarding stimuli (Rolls, 2007) and increased activation in these regions is associated with motivation and the regulation of goal-directed behavior (Harsay et al., 2011).

Considering that self-control tasks are regarded as highly effortful, demanding, and aversive (Muraven et al., 1998), particularly when self-control resources are relatively scarce as they are under conditions of ego-depletion, we hypothesize that a glucose mouth rinse prior to engaging in a self-control task will moderate the deleterious effects of self-control resource depletion. Just as the endurance time trial used as the dependent measure of performance in Chambers et al.'s (2009) and others' studies using the mouth-rinse method is "a demanding form of exercise during which power output typically declines steadily before a final sprint to the finish" (p. 1788), so self-control tasks are considered particularly arduous and individuals performing such tasks experience substantial fatigue that requires considerable motivation and effort to overcome. Based on the findings of oral glucose sensing studies in exercise physiology, we propose that administering a glucose mouth rinse will enable depleted individuals to overcome the deleterious effects of self-control resource depletion.

Our hypothesized moderation of self-control resource depletion by oral glucose sensing may be the result of a number of two possible mechanisms. First, oral glucose sensing may facilitate activity in regions of the brain required for effective self-control and counteract the decreased activity in these regions observed when individuals perform self-control tasks under conditions of depletion. There is evidence that ego-depletion coincides with reduced activity in a brain region shown to be activated by oral glucose, the ACC. The ACC has been found to govern a number of processes important for self-control such as conflict monitoring (Botvinick, Cohen, & Carter, 2004; Inzlicht & Gutsell, 2007) and the need for cognitive control (Heatherton, 2011; Lorist, Boksem, & Ridderinkhof, 2005). Research has shown that engaging in tasks that require self-control, such as the Stroop color-naming task (Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000) and the handgrip strength task (Liu et al., 2003), is associated with activation in the ACC. In addition, electroencephalographic (EEG) studies have found an attenuation of activity in the neural pathways associated with conflict monitoring, the process by which individuals detect and respond to mismatches in actual and intended responses, during performance of self-control tasks under conditions of depletion and mental fatigue (Inzlicht & Gutsell, 2007; Lorist et al., 2005). Activation of the conflict-monitoring system is associated with peaks in error-related negativity (ERN), an EEG waveform isolated in the ACC in neuroimaging studies (van Veen & Carter, 2002). Weaker ERN signals have been found in participants performing a Stroop task after the prior depletion of self-control resources compared to non-depleted controls (Inzlicht & Gutsell, 2007). It seems that the ACC may play an important role in mediating performance on tasks requiring self-control. Given that deficits in ACC activity are observed after prior self-control resource depletion, we propose that a mechanism by which the sensing of oral glucose improves self-regulatory performance is through the stimulation of ACC activity. This stimulation may serve to counteract the reduced ACC activity associated with fatigue on self-control tasks under conditions of resource depletion.

A second potential mechanism is that oral glucose acts as a rewarding stimulus promoting increased motivation due to its action on the dopaminergic system of the ventral striatum. Research has shown that activity in the ventral striatum corresponds with reward-induced motivation in individuals performing physical (handgrip strength) and cognitive (Stroop) self-control tasks (Schmidt, Lebreton, Clery-Melin, Daunizeau, & Pessiglione, 2012). It is plausible that the activation of the ventral striatum as a result of oral glucose sensing may lead to increased motivation toward self-control tasks, possibly by signalling a heightened reward value of the task. This additional value may assist in individuals overcoming the fatigue experienced on tasks when self-control resources are depleted. The explanation is similar to the mechanism proposed by Chambers et al. (2009) who proposed that oral glucose sensing improved performance on endurance tasks by counteracting the inhibition of activity in the dopaminergic pathways of the ventral striatum, a proposed cause of ‘central’ fatigue (Chaudhuri & Behan, 2000). According to Chambers et al., this effect may be similar to the action of stimulants such as caffeine and amphetamine, which have been shown to activate similar reward pathways in the brain (Garrett & Griffiths, 1997) and promote increased performance on tasks involving self-control (Lorist, Snel, Kok, & Mulder, 1994)[1].

Oral glucose sensing may provide an alternative account for Gailliot et al.’s (2007) findings on glucose ingestion and self-control. As the glucose solution in their studies had to pass through the mouth, our hypothesis that that the oral sensing of glucose led to the observed increase in self-control resource capacity in their studies, rather than the metabolism of the glucose itself, is a plausible one. Of course, as the glucose was ingested in Gailliot et al.’s studies, a metabolic explanation for their findings cannot be unequivocally ruled out. In the present study we propose to test this alternative hypothesis by examining the effect of oral glucose on self-control resource depletion[2]. We plan to adopt the glucose mouth-rinse procedure (Carter et al., 2004), in which glucose is introduced to the oral cavity but not ingested, to examine whether the presence of glucose stimulates improved performance on self-control tasks after self-control resource depletion. To the extent that the glucose mouth rinse attenuates the deleterious effect of self-control resource depletion on task performance as opposed to a placebo rinse, we will have support for a centrally-mediated rather than metabolic mechanism for the effect of oral glucose supplementation on self-control.

Overview of Current Research

We report on five experiments examining the effect of a glucose mouth rinse on post-depletion self-control in tasks from number of domains of self-control. In the first three studies participants were asked to engage in an initial task that depletes self-control. Next, participants were asked to rinse their mouths with either a solution containing glucose or a placebo solution containing artificial sweetener. Participants were then asked to complete a second self-control task, performance on which represented our dependent measure of self-control. If our hypothesis that the moderating effect of glucose on self-control capacity after depletion is due to its sensing in the mouth rather than its ingestion and metabolism, we predicted that participants receiving the glucose mouth rinse would perform significantly better on the second self-control task than participants receiving the placebo. In the final two studies, we aimed to extend our work by introducing a no-depletion condition alongside the depletion condition. We hypothesized that a glucose mouth rinse would only improve individuals' self-control resources if they were depleted beforehand. We therefore expected the moderating effect of the glucose mouth rinse on performance on the second self-control task would be confined to the depletion condition. The research is unique as we expect to provide evidence for our alternative explanation of Gailliot et al.'s (2007) suggestion that the metabolism of ingested glucose in the brain promotes better self-control. In terms of mechanisms, we speculate that the oral sensing of glucose stimulates brain regions associated with reward, motivation and motor control, which may reverse the deficits in neural processes implicated in self-control failure and stimulate increased motivation to exercise self-control on tasks when depleted.

Study 1

The purpose of Study 1 was to provide preliminary evidence that the presence of a glucose-containing solution in the oral cavity would moderate the depletion of self-control resources. Participants were asked to engage in an initial task that required self-control by resisting the temptation to eat an appetizing food (Baumeister et al., 1998). After completing this task, participants were randomly allocated to an experimental condition in which they rinsed their mouths with a solution that contained either glucose or an artificially-sweetened placebo before spitting it out. They then engaged in a second self-control task. We hypothesized that participants rinsing their mouth with glucose would exhibit better performance on the second task than participants who rinsed their mouth with an artificially-sweetened placebo.

Method

Participants. Participants were 30 female undergraduate and postgraduate students enrolled in psychology degree programmes. Participants received a payment of $10 in advance for their participation. On recruitment, participants were asked to refrain from eating three hours prior to the experiment as nutritional status has been shown to interfere with neural responses to the presence of an oral glucose stimulus (Jeukendrup & Chambers, 2010). Data from three participants were not used in the analyses, one refused to eat the food offered in the taste perception task and the other two did not comply with instructions for the handgrip task.

Procedure. Participants were shown into a laboratory and informed that they were participating in a study examining taste preferences. They were initially asked to squeeze a commercially-available handgrip apparatus of the type used in previous studies to measure self-control capacity (e.g., Muraven et al., 1998). The task requires self-control exertion as an individual is compelled to resist the temptation to relinquish his or her grip as a result of the discomfort in the forearm muscles. Participants were asked to squeeze the handles of the apparatus together using their dominant hand with sufficient force to hold a coin between the handles for as long as possible. Time spent on the handgrip task constituted the dependent measure of self-control performance. As performance on the task is also dependent on grip strength, an initial baseline measure was taken to control for individual differences in grip strength. As a cover story to mask any link between the handgrip task and the other aspects of the experiment, participants were told that the handgrip task was to provide another researcher with pilot data for an unrelated study.

After completing the initial handgrip task, participants were asked to participate in a taste perception task. Participants were seated behind a desk upon which two plates of food were placed: a plate of appealing, freshly-baked cookies and a plate of unappealing, raw radishes. Participants were asked to taste the radishes only and explicitly told to ignore the cookies. As part of the cover story, participants were told that they would be contacted 24 hours later and asked their perception of the food they had tasted. The experimenter then left the room for 5 minutes reminding the participants that they were to taste the radishes only and avoid the cookies before leaving. After the allotted time had elapsed, the experimenter returned to the room and removed the plates of food. Participants were then presented with a plastic cup containing exactly 100ml of solution and asked to rinse their mouth with the solution for 10 seconds and spit it into an accompanying empty cup. The volume of expectorate was measured to ensure that participants did not ingest any of the solution. Participants assigned to the glucose condition rinsed their mouth with an 18% solution and participants assigned to the placebo condition received a solution containing a non-caloric artificial sweetener (aspartame).

We conducted a pilot study prior to the experiment to identify the amount of placebo required to produce a solution that was not discernible in sweetness or perceived sugar content to an 18% glucose solution[3]. A double blind procedure was used to ensure that neither the participants nor the experimenter were aware of the content of the solutions during the experiment. Participants then completed a brief questionnaire asking them to rate the solution for sweetness, pleasantness, consistency, and palatability on 7-point scales.

Next, participants were asked to complete the handgrip task for a second time, which was to serve as the dependent measure of self-control. They were again told that this was as a favor for another researcher who wanted to test the consistency of their pilot data. Finally, the experimenter administered the Brief Mood Introspection Scale (BMIS, Mayer & Gaschke, 1988) and a measure of trait self-control (Tangney et al., 2004). The experimenter then administered a funnel debrief procedure in which participants were probed for a suspected link between the handgrip and taste perception tasks prior to receiving a full debrief after which they were thanked and dismissed.

Results and Discussion

As the values for time spent on the handgrip task were positively skewed, we used square-root transformations of the values in our analysis to correct for violations of the assumption of normality (McClelland, 2000). We conducted a one-way ANCOVA on handgrip task duration with mouth-rinse solution (glucose vs. placebo) condition as the independent variable and controlling for baseline handgrip duration. As shown in Figure 1, participants rinsing their mouths with glucose solution spent significantly longer on the handgrip task than those who rinsed their mouth with placebo solution, $F(1,24) = 8.42$, $p = .008$, $\eta_p^2 = .26$[4]. There were no significant differences across the mouth-rinse conditions on taste perceptions of the solutions or BMIS scores (all *t*s < 1.08). None of the participants reported a link between the self-control tasks. There was also no discernible difference in the volume of solution expectorated after rinsing and the initial mouthful volume (computed by difference from the initial cup volume) rinsed by the participant. Finally, reanalysing the data including trait-self-control as a covariate revealed an identical effect for the mouth-rinse condition and no effect of trait self-control.

Results provided preliminary support for our hypothesis that the presence of glucose in the oral cavity counteracts the deleterious effects of self-regulatory resource depletion. Resisting the temptation to eat the palatable cookies and tasting the bland radishes instead was hypothesized to consume self-control resources. Participants rinsing their mouth with a glucose-containing solution exhibited significantly better performance on the handgrip task than those who rinsed with an artificially-sweetened placebo solution. These findings were independent of taste perceptions, mood changes, and trait self-control.

Studies 2 and 3

Studies 2 and 3 were designed to provide conceptual replications of Study 1 and provide further evidence that a glucose mouth rinse mitigated the debilitating effects of self-control resource depletion. In both studies participants engaged in an initial task that depleted their self-control resources. In Study 2 participants were asked to read a boring passage of text in an expressive fashion. Reading a passage of text in an emotionally-expressive manner required self-control as participants had to actively control their emotions and expressions and overcome the tendency to read passage in their natural manner. In addition, reading the tedious material in such an expressive manner was incongruous with its content and, therefore, required participants to act counter-attitudinally, which has also been proposed to deplete self-control resources (Baumeister et al., 1998). In Study 3 participants were asked to engage in an unsolvable figure-tracing task. Participants were required to make multiple attempts to replicate a geometric figure using tracing paper for which the solution is impossible. The task is aversive and frustrating and demands considerable self-control to overcome the desire to quit (e.g., Baumeister et al., 1998).

Subsequent to the initial task participants completed the mouth rinse procedure, identical to the one used in Study 1, in which they were required to rinse their mouth, but not ingest, either a glucose or placebo solution. Finally, participants completed follow-up tasks that required self-control. In Study 2 participants had to complete an unsolvable anagram task. Persisting with the task required resisting the temptation to quit in the face of repeated failure and the frustration of the goal of finding a solution (Baumeister et al., 1998). In Study 3 participants were encouraged to consume a healthful but noxious-tasting drink. Consuming an aversive-tasting drink requires individuals to overcome the natural tendency to avoid such an unpleasant activity even if there is good reason to do so (Muraven & Slessareva, 2003). The extent to which participants' receiving a glucose mouth rinse performed better on the follow-up self-control tasks relative to those receiving an artificially-sweetened placebo mouth rinse was expected to provide further confirmation that glucose in the oral cavity alleviates self-control resource depletion.

Method

Participants. Participants were undergraduate students enrolled in psychology degree programs (Study 2: *N* = 32, 21 female; Study 3: *N* = 34, 20 female) who received a $10 allowance in advance in return for their participation. Participants were again told to refrain from eating three hours prior to participation.

Procedure. Participants were shown into a laboratory and informed that they were participating in a study examining the relationship between task performance and taste perception. Participants then completed the initial self-control task.

Participants in Study 2 were seated at a desk in front of a video camera and asked to read out a tedious three-page passage from a safety guidelines handbook. As a cover story, participants were informed that oral presentation was an important skill relevant to many professions and that they were taking part in a trial measure of that skill. They were told to read the text in an emotionally-expressive and enthusiastic manner and to “really get into it”. They were also informed that their reading would be videotaped for quality control purposes. The experimenter asked the participant to begin reading and left the room for 5 minutes.

Participants in Study 3 were seated behind a desk and asked to participate in a problem-solving task. The task required the participant to trace a geometric figure without retracing any lines or lifting his or her pen from the paper. Participants were initially given instructions on how to solve the tasks and presented with two practice figures to familiarize themselves with the task. They were given multiple pieces of tracing paper and told that they could make as many attempts as necessary to solve the figure. The experimenter then gave participants the two test figures and told them that they could take as much time as they liked to solve the figures but that they could stop before they finished by ringing a buzzer. The experimenter then left the room and observed participants covertly to ensure that they engaged in the task. All participants were stopped after 30 minutes and only one participant had not sounded the buzzer prior to this cutoff time. After completion of these tasks, participants in both studies received the glucose or placebo mouth-rinse using a double-blind procedure followed by the taste perception measures.

Last, participants engaged in the second dependent self-control task. In Study 2, participants were asked to solve a series of anagrams (Ciarocco, Sommer, & Baumeister, 2001). As a cover story, participants were told that the anagram task constituted a pilot of materials for another study. Participants were given instructions on how to solve anagrams by the experimenter and given two practice anagrams to try for 2 minutes. The experimenter then administered the six test anagrams, told participants they could spend as long as they liked on the anagrams but could stop before doing so by pressing a buzzer, and left the room. Unbeknown to the participant, three of the test anagrams were unsolvable. The experimenter stopped participants after 20 minutes of they had not sounded the buzzer. In Study 3, participants were encouraged to drink as much as possible of a noxious, but harmless, drink (Muraven & Slessareva, 2003). Participants were presented with a series of 20 small plastic cups containing 50ml of a drink made of 2 parts vinegar and 1 part concentrated orange juice. The drink was noxious in taste but harmless. As a cover story, participants were told: “We would like you to try this trial health drink. It does not taste particularly pleasant. However, it is good for you. How much you drink is up to you.” Time spent on the anagram task (Study 2) and the amount of noxious drink consumed (Study 3) constituted the dependent measure of self-control in each study respectively.

Finally, the experimenter asked participants to complete the BMIS and trait self-control measure and administered the funnel debrief procedure after which participants were thanked and dismissed.

Results and Discussion

We conducted a one-way ANOVA to test the effect of mouth-rinse solution (glucose vs. placebo) condition on the dependent measures of self-control. As shown in Figure 2, participants rinsing their mouths with glucose solution performed significantly better on the anagram task (Study 2, $F(1,30) = 6.12$, $p = .019$, $\eta_p^2 = .17$) and consumed significantly more of the noxious drink (Study 3, $F(1,32) = 4.06$, $p = .05$, $\eta_p^2 = .11$)[5] than those who rinsed with placebo solution. There were no significant differences across the glucose and placebo conditions on taste perceptions of the solutions or BMIS scores in both studies (all *t*s < 1.21). In both studies, participants did not identify a link between the self-control tasks and there was no difference between the expectorate and initial mouthful volume of the solution rinsed by the participants. Reanalysing the data using a one-way ANCOVA with trait self-control as a covariate revealed an identical pattern of effects with no significant effect for trait self-control in either study. Results of both studies provide additional support for our hypothesis that a glucose mouth rinse leads to improved self-control among depleted individuals relative to those administered an artificially-sweetened placebo.

Study 4

While Studies 1-3 provide converging evidence that the presence of glucose in the oral cavity leads to better self-control among individuals whose self-control resources had been depleted, we did not include a no-depletion condition. Our hypothesis in the present investigation was that the facilitative effect of the oral glucose rinse on task performance would be exclusive to self-control tasks. This is because we assumed, consistent with the limited resource model, that self-control tasks place considerable demand on the systems responsible for behavioral regulation and impulse control leaving them diminished when it comes to doing subsequent tasks. A glucose rinse may help overcome the state of depletion by stimulating these systems. We would therefore expect to see no effect of the glucose rinse on self-control in non-depleted participants and a significant interaction between the depletion and mouth rinse conditions such that a glucose rinse only facilitated self-control in depleted participants.

It is possible, however, that the presence of oral glucose sensing leads to increased performance on any task, independent of depletion. In this case we would expect to see a main effect of glucose rinse on second-task performance and no mouth rinse x depletion interaction. This suggests that effect of oral glucose on task performance may be one that is generally motivational and not exclusive to tasks requiring self-control. Of course it is also possible that both effects exist such that oral glucose sensing has facilitative effects on both types of task but also interacts with depletion leading to greater improvements in second task performance post-depletion than its effect on the tasks alone. Our aim in Study 4 was to test these alternative possibilities by including a no-depletion condition.

Participants received either a task that required self-control (depletion) or a task that did not require self-control (no depletion) following Baumeister et al.'s (1998) dual-task procedure. Thereafter they were randomly allocated to rinse their mouths with, but not ingest, a solution containing either a glucose or artificially-sweetened placebo. In keeping with the findings of Studies 1-3, we expected participants allocated to the depletion condition who rinsed their mouths with a glucose solution would perform significantly better on the second self-control task than those who rinsed with a placebo solution. Importantly, depleted participants receiving a glucose mouth rinse should perform as well on the second task as non-depleted participants regardless of mouth rinse condition. These effects were proposed to be manifested in a significant interaction between mouth rinse and depletion conditions.

Method

Participants. Participants were 48 high-school students (32 female) in their final year before graduation and received a payment of $10 in advance in return for their participation. As in Studies 1-3, participants were asked to refrain from eating three hours prior to participation. Data from three participants were omitted from analyses, one failed to follow the instructions for the Stroop task correctly and the other two reported having eaten within three hours of the experiment.

Procedure. Participants were shown into a laboratory and informed that they were participating in a study investigating problem solving and taste perceptions. Participants initially completed a handgrip task to provide a baseline measure of handgrip strength and were presented with the same cover story as Study 1. Using a dual-task paradigm, participants were randomly assigned to receive an initial task that either required self-control (depletion condition) or did not require self-control (no-depletion condition). Participants assigned to the depletion condition completed an incongruent version of the Stroop color-naming task. In this task, participants were presented with a series of color-words printed in colored ink so that the meaning of the word and ink color conflicted (e.g., the word “blue” written in green ink). Participants were required to name the color of the ink and not read the word. This task has been acknowledged as one that requires self-control resources as participants have to suppress the impulse to read the word, a more automatic response, rather than name the color of the ink, a less automatic one; a task made particularly challenging due to the processing interference caused by the conflict between the word meaning and ink color (Webb & Sheeran, 2003). The words were presented in a random order on a CRT screen controlled by Eprime experimental software. Responses were made using keys corresponding to three colors (red, green, and blue) on the computer keyboard with participants receiving a total of 90 words, randomly presented. Participants assigned to the no-depletion condition received a congruent version of the Stroop task in which there was no conflict between meaning of the color-words and the ink in which they were written. Next, participants completed a manipulation check by rating their level of fatigue on a 7-point scale ranging from 1 (*not tired at all*) to 7 (*extremely tired*) and also completed the BMIS.

Participants were then randomly assigned to receive the glucose or placebo mouth rinse using a double-blind procedure followed by the taste perception measures. Finally, participants completed the handgrip task for a second time, performance on which constituted the dependent measure of self-control. Participants completed the measure of trait self-control before being taken through the funnel debrief procedure, thanked, and dismissed.

Results and Discussion

Preliminary analyses. Participants in the depletion condition reported significantly higher fatigue levels (M = 4.32, SE = 0.24) relative to participants in the no-depletion condition (M = 3.04, SE = 0.29), $t(43) = 3.37$, $p = .002$, $d = 1.00$) providing evidence that the Stroop task was successful in inducing depletion. There were also no differences in sweetness, pleasantness, consistency, and palatability ratings of the solutions across the mouth-rinse conditions and no differences in BMIS scores across the depletion conditions (*ts* < 1.50). There were no differences in volume of expectorate and rinsed volumes of the solutions and there was no suspicion of a link between the initial and dependent tasks. As in Study 1, we corrected for violations of normality by conducting a square-root transformation of the handgrip task duration (McClelland, 2000).

Self-control. A 2 (self-control depletion: depletion vs. no depletion) x 2 (mouth-rinse condition: glucose vs. placebo) ANCOVA on handgrip task duration controlling for baseline handgrip strength revealed a significant main effect for mouth rinse condition, $F(1,40) = 19.39$, $p < .001$, $\eta_p^2 = .33$. However, this effect was qualified by a significant depletion x mouth rinse interaction effect, $F(1,40) = 10.32$, $p = .003$, $\eta_p^2 = .21$[6]. Results are presented in Figure 3. Simple effects analyses revealed that depleted participants who received a glucose mouth rinse performed significantly better on the handgrip task compared to those who received a placebo rinse, $F(1,40) = 28.34$, $p < .001$, $\eta_p^2 = .41$. Among participants receiving the placebo mouth rinse, those assigned to the no-depletion condition performed significantly better on handgrip task relative to those assigned to the depletion condition, $F(1,40) = 9.88$, $p = .003$, $\eta_p^2 = .20$[7]. In addition, among non-depleted participants, there was no significant difference in handgrip performance across the mouth-rinse conditions, $F(1,40) = 0.76$, $p = .39$, $\eta_p^2 = .02$. Reanalysing the data including trait self-control as a covariate revealed no significant effect for trait self-control.

Findings provide further corroboration for our hypothesis that oral glucose attenuates the depletion of self-control resources. Furthermore, results confirm our expectation that the effect is confined to individuals whose self-control resources have been depleted as a result of a previous task and does not affect self-control capacity in participants whose self-control resources have not been depleted.

Study 5

The purpose of Study 5 was to provide a replication of Study 4 using different depleting and dependent self-control tasks. Using a dual-task paradigm, we depleted participants' self-control resources using a complex counting task that required participants to overcome the dominant tendency to deal with one computational operation at a time and coordinate multiple operations instead (Webb & Sheeran, 2003). Participants in the no-depletion control condition engaged in a simple counting task used in previous dual-task paradigm experiments and considered non-depleting (Hagger et al., 2010; Muraven et al., 1998). Participants then completed the mouth-rinse procedure used in the previous studies. Our measure of self-control capacity was performance on the incongruent version of the Stroop task. In keeping with our primary hypothesis, we predicted that depleted participants receiving a glucose mouth rinse would perform significantly better on the Stroop task (i.e., have reduced response latency) relative to those receiving a placebo rinse. We also expected no differences in self-control task performance for participants allocated to the no-depletion condition, regardless of mouth-rinse condition. It is expected that this study will provide additional support for the mouth-rinse x depletion interaction effect found in Study 4.

Method

Participants. Participants were 40 undergraduate university students (28 female) enrolled in a psychology degree program and were given $10 in advance in return for their participation. As in the previous experiments, participants were asked to refrain from eating three hours prior to participation.

Procedure. Participants were shown into a laboratory and informed that they were participating in a study investigating problem solving and taste perceptions. Using a dual-task paradigm, participants were asked to complete an initial counting task. They were instructed to stand upright on two legs and count backward from 1000 in multiples of five, a task we expected participants to find relatively straightforward, for a period of three minutes. Next, participants allocated to the depletion condition were asked to stand on one leg, and count backwards from 1000 in multiples of seven. This task was expected to be far more challenging as participants would be obliged to overcome the recently-learned counting rules as well as cope with the additional coordination element of the task. Participants were told that they needed to be mindful of their accuracy and, if they lost their balance, they would have to start counting over from the beginning. The experimenter remained in the laboratory to verify counting accuracy and time the participants. Participants allocated to the control group were asked to restart the original counting task from the beginning. Participants were given no feedback during the course of the counting task. After 5 minutes, participants were stopped, invited to sit down, and asked to complete measures of effort (1 = *no effort at all* to 7 = *very effortful*), fatigue (1 = *not tired at all* to 7 = *extremely tired*), and difficulty (1 = *not difficult at all* to 7 = *extremely difficult*), and the BMIS.

The experimenter then administered the glucose or placebo mouth-rinse using a double-blind procedure, followed by the taste perception measures. Next, participants were asked to complete an incongruent version of the Stroop task, identical to the version used to deplete self-control resources in Study 4. This constituted our dependent measure of self-control. Participants were presented with a cover story to mask any relation between the Stroop and counting tasks. After completing the task, participants were asked to complete the trait self-control measure, subjected to the funnel debrief procedure, thanked, and dismissed.

Results and Discussion

Preliminary analyses. Participants allocated to the depletion condition reported significantly higher fatigue (M = 4.95, SE = 0.32), effort (M = 6.05, SE = 0.24), and difficulty (M = 5.40, SE = 0.32) after the counting task relative to participants in the no-depletion condition (fatigue M = 3.75, SE = 0.33; effort M = 5.30, SE = 0.23; difficulty M = 3.50, SE = 0.36; all ts > 2.60, ps < .032, ds > 0.72) indicating that counting task had been successful in inducing depletion. No differences were found on the sweetness, pleasantness, consistency, and palatability ratings across the mouth rinse conditions and no differences in BMIS scores across the depletion conditions (ts < 1.7). In addition, we found no differences in the volume of the expectorated solution and the volume of fluid rinsed by participants. Participants did not suspect any relationship between the initial and dependent tasks.

Self-control. A 2 (self-control depletion: depletion vs. no depletion) x 2 (mouth-rinse condition: glucose vs. placebo) ANOVA on Stroop task response latency revealed a significant main effect for depletion condition, $F(1,36) = 7.73$, $p = .009$, $\eta_p^2 = .18$. This was qualified by a significant depletion x mouth rinse interaction, $F(1,36) = 7.28$, $p = .011$, $\eta_p^2 = .17$. Results are presented in Figure 4. Probing the interaction using simple effects analyses revealed that depleted participants that received a glucose mouth rinse exhibited significantly faster response latencies on the Stroop task compared to those that received the placebo rinse, $F(1,36) = 5.04$, $p = .031$, $\eta_p^2 = .13$. Furthermore, among participants that received the placebo mouth rinse, those assigned to the no-depletion condition responded significantly faster to the Stroop task compared to those assigned to the depletion condition, $F(1,36) = 15.01$, $p < .001$, $\eta_p^2 = .29$[8]. In addition, among non-depleted participants, there was no significant difference in performance on the Stroop task across the mouth rinse conditions, $F(1,36) = 2.47$, $p = .125$, $\eta_p^2 = .06$. Finally, we conducted the analysis using an ANCOVA with trait self-control as a covariate. In contrast to previous studies we also found a significant effect for trait self-control, $F(1,35) = 5.74$, $p = .022$, $\eta_p^2 = .14$[9].

Findings are consistent with those of Study 4 and our overall hypothesis that rinsing the oral cavity with glucose results in better self-control, but only among participants whose self-control resources have been depleted. Furthermore, the findings were independent of the effect of individual differences in trait self-control and were not the result of the induction of a positive mood or perceived sweetness of the solutions.

General Discussion

The purpose of the present investigation was to test the hypothesis that the presence of glucose in the oral cavity moderates the deleterious effects of self-control resource depletion on self-control task performance. Adopting a resource-depletion approach and basing our hypotheses on research from exercise physiology and behavioral neuroscience, we predicted that rinsing the mouth with glucose without ingestion would promote better self-control when depleted. We proposed that this would provide support for a centrally-mediated mechanism underpinning the effect of glucose supplementation on self-control as opposed to previous explanations based on glucose metabolism in the brain. In five studies using tasks from different domains of self-control, we demonstrated that post-depletion self-control task performance was significantly better among participants who rinsed their mouth with a glucose solution relative to participants who rinsed their mouth with an artificially-sweetened placebo solution. In Studies 4 and 5 we further demonstrated that the facilitation effect was confined to participants whose self-control resources were depleted. Participants who engaged in a non-depleting initial task, regardless of whether they received a glucose or placebo mouth rinse, performed as well on a second self-control task as depleted participants that received a glucose mouth rinse. We also demonstrated that the effects were independent of trait self-control and positive and negative affect.

Our results stand in contrast to previous explanations for the effect of oral glucose supplementation on self-control after depletion. Gailliot et al. (2007) contend that it is the metabolism of glucose in the brain, and the supply of blood glucose to the brain, that promotes better self-control after oral glucose supplementation. According to their explanation, self-control tasks are very costly in terms of glucose consumption by the brain and temporary drops in brain glucose levels lead to self-control resource depletion. Data from their laboratory supporting this explanation identified variations in blood glucose in participants engaging in self-control tasks and that oral glucose supplementation leads to better self-control in depleted individuals. They did not, however, measure glucose levels in the blood or brain in their supplementation studies. Furthermore, there is evidence that variations in blood glucose levels do not necessarily reflect variations in brain glucose levels, which tend to be relative stable, leading to some authors to question the explanation that metabolism of brain glucose is responsible for the effect (Beedie & Lane, 2011; Kurzban, 2010).

Our findings provide an alternative explanation that not only provides a suggested mechanism independent of glucose metabolism, but also accounts for the increasing body of research that has shown significant improvements in self-control as a result of oral glucose supplementation (e.g., DeWall et al., 2008; Dvorak & Simons, 2009; Gailliot et al., 2007; Masicampo & Baumeister, 2008). As ingestion of a glucose solution in previous supplementation studies means that it will be present in the oral cavity, albeit for a short period of time, it is also likely to lead to the sensing of the glucose in the oral cavity and facilitation of self-control performance through a central mechanism. Of course, it is possible that when drinking a glucose solution, the solution does not linger sufficiently in the mouth for oral receptors sensitive to glucose to detect the solution to the same extent as the mouth-rinse procedure we used in the current study. We cannot, on the strength of the current data alone, unequivocally rule out the possibility that the moderating effect of oral glucose supplementation on self-control resource depletion observed in previous studies is also due, in part, to the metabolism of glucose. We are confident, however, that the effect in our studies is not due to glucose metabolism as, even if participants had ingested any glucose, we did not allow sufficient time for the glucose to be assimilated and enter the bloodstream. Future experiments should include the addition of both rinsing and ingestion conditions in parallel to test whether both methods lead to an identical pattern of effects on self-control resource depletion.

Research in the fields of exercise physiology and behavioral neuroscience point to possible mechanisms that may account for better self-control observed in depleted participants receiving a glucose mouth rinse in the present research. Neuroimaging data indicate that the presence of glucose in the oral cavity is associated with increased activation in the ACC and ventral striatum; brain regions associated with reward, motivation, and the regulation of motor activity (Chambers et al., 2009). We propose that the activation of these regions may lead to more effective self-control when depleted through two possible mechanisms. First, the oral sensing of glucose may counteract deficits in the neural pathways that govern self-control processes. Performance on self-control tasks in numerous domains has been shown to coincide with ACC activation (e.g., Leung et al., 2000; Liu et al., 2003). There is also evidence that fatigue and failure on self-control tasks under conditions of resource depletion is associated with weakened ERN potentials, EEG waveforms associated with ACC activity (Inzlicht & Gutsell, 2007). As the ACC is one of the unique brain regions stimulated by oral glucose as opposed to artificially-sweetened placebo, the superior performance of depleted participants who received a glucose mouth rinse could be due to increased activation in the ACC. This activation may counteract the decreased activity in this region associated with self-control performance under depletion and facilitate the processes controlling self-control task performance like conflict monitoring. Second, oral glucose may increase motivation to engage in tasks by providing a rewarding stimulus. This follows from research that has demonstrated increased activity in the dopaminergic pathways of the ventral striatum when performing tasks that require self-control (Schmidt et al., 2012). Glucose may therefore signal increased reward value associated with the self-control task and promote increased effort and motivation on the task.

As the ACC and ventral striatum are both implicated in motivation and regulation of goal-directed behavior (Devinsky, Morrell, & Vogt, 1995), it is possible that the proposed mechanisms for the effect of sensing oral glucose on self-control task performance are not mutually exclusive. There is evidence that cognitive tasks requiring self-control involve multiple processes that are mediated by both brain regions (Prevost, Pessiglione, Metereau, Clery-Melin, & Dreher, 2010) and failure on these tasks coincides with decreased activity in these regions (Inzlicht & Gutsell, 2007; Lorist et al., 2005). Summarising these findings, Lorist et al. (2005) contend that “mental fatigue results from a failure to maintain adequate levels of dopaminergic transmission in the striatum and ACC” (p. 204). The effect of oral glucose in increasing activity in both brain regions may, therefore, be involved in attenuating the effects of depletion on self-control task performance in the current research.

It is important to note that the activation of these regions is confined to solutions containing sugar and does not occur in response to artificial sweetener; no activation of the ACC and ventral striatum has been observed in participants rinsing their mouths with a solution containing a non-caloric artificial sweetener (Chambers et al., 2009; Frank et al., 2008). The effect, therefore, appears to be independent of the sensing of sweetness per se. This provides a reason why participants receiving the placebo mouth rinse in the present study did not exhibit better self-control under conditions of depletion. Of course we must stress that these proposed mechanisms remain speculative and unverified as we did not include measures of neural responses to oral glucose supplementation in our studies. Furthermore, the precise neurological processes by which the increased ACC and ventral striatum activity stimulated by oral glucose may act on self-control task performance under depletion have yet to be elucidated. Bray et al. (2012) suggest that “a question that remains unanswered is what physiological (e.g., neurochemical, neuroelectrical) mechanisms are affected by ACC activation during effortful or centrally fatiguing tasks” (p. 199). Future research should replicate the current studies using neuroimaging (e.g., EEG, fMRI) and psychophysiological techniques to examine the neural and biochemical responses of individuals receiving a glucose mouth rinse under conditions of depletion.

An important question raised in the current study is why oral glucose did not improve performance on the second self-control task for all participants, independent of depletion. The reason may lie in the fact that the relative level of effort on self-control tasks is exacerbated when resources are depleted compared to when they are fully intact. Performing self-control tasks when depleted is extremely arduous and requires more effort than when one is not (Muraven & Slessareva, 2003). In addition, individuals have the tendency to conserve or ‘hold back’ resources when depleted (Muraven, Shmueli, & Burkley, 2006). Participants receiving a non-depleting initial task would have had sufficient resources to expend on the second task as they were relatively ‘fresh’; motivation was likely to be high and perceptions of fatigue low. Depleted participants, on the other hand, would have experienced increased fatigue and decreased motivation on the second task due to the mismatch between task demand and self-control resource availability. As oral glucose sensing is proposed to improve task performance by counteracting impairment of the neural processes of self-control and increasing motivation, depleted individuals rinsing with glucose may have been compelled to access and commit the remaining available resources to performing the task, which would have otherwise been conserved. In contrast, non-depleted participants would have had sufficient resources to engage in the tasks and, therefore, increased motivation to commit resources stimulated by oral glucose is less likely to have been effective in improving self-control as there was no lack of availability.

Conclusions and Recommendations for Future Research

In conclusion, our research provides a new perspective on the role of glucose supplementation on self-control from a resource-depletion perspective. Self-control tasks are unique in that they incur a substantial cost to individuals due to the need to allocate limited resources to complete them successfully. This means that there may be insufficient resources available, or a reduced ability to allocate remaining resources, to engage in continued self-control efforts. We have shown that the presence of glucose in the oral cavity serves to moderate self-control resource depletion, possibly by signalling increased activity in regions of the brain associated with reward, motivation, and regulation of motor activity. This may also provide an alternative account for the moderating effects of oral glucose supplementation on self-control observed previously because ingestion of a glucose solution also requires it to pass through the mouth. While our findings are consistent with the predictions of the resource depletion account, they also contribute to an increasing literature that glucose may not be a candidate physiological analog for self-control resources. Instead, ego-depletion may be due to problems of self-control resource allocation rather than availability (Beedie & Lane, 2011).

Recent findings indicate that individual differences in beliefs about self-control (Job, Dweck, & Walton, 2010) and the provision of consistent and misleading feedback regarding the state of self-control resources (Clarkson, Hirt, Jia, & Alexander, 2010) also affects self-control task performance under conditions of depletion. These findings provide evidence that self-control resource depletion may be partly due to cognitive beliefs about willpower as opposed to the depletion of resources mediated by a physiological mechanism such as glucose availability. The research groups behind these studies suggest that their findings indicate that self-control resource depletion may be a function of both cognitive and physiological processes. Current findings fuel this debate further by providing evidence that the effects of glucose in moderating self-control resource depletion are the result of centrally-mediated processes in the brain rather than metabolic processes. Although the processes are likely to differ, it seems that beliefs about resources and oral glucose sensing may affect self-control performance independent of a biological resource. We look to future research to examine the interactive effects of oral glucose sensing and beliefs about self-control on ego-depletion.

Future research should also seek to test and apply current findings in the field. Given that self-control can be bolstered by the mere presence of glucose in the oral cavity, this might be of important practical value for people in situations where they might experience lapses in self-control. A glucose mouth rinse may therefore be very useful to those who are constantly attempting to regulate their behavior (e.g., dieters, smokers) or are frequently having to exert self-control (e.g., workers employed to engage in boring or difficult tasks). If individuals are made aware of the situations in which their resources may be depleted, they may be able to boost their self-control by introducing glucose into the oral cavity. Furthermore, research is needed to establish whether effects of oral glucose on self-control are specific to a glucose-containing mouth rinse or could be administered by more practical means, such as candy or glucose-infused chewing gum. Given that the glucose does not have to be ingested for it to promote self-control, the use of a mouth rinse, or a validated alternative means of introducing glucose into the oral cavity, is extremely useful as it may not conflict with other goals e.g. individuals attempting to lose weight or reduce sugar intake.

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Footnotes

[1] An additional possible mechanism is that oral glucose sensing signals the availability of metabolic fuel and serves as a stimulus to expend more resources when engaged in self-control tasks. We considered this mechanism implausible as there is no evidence that the sensing of oral glucose stimulates the hormonal and neural systems responsible for controlling energy balance. A full discussion of this proposed mechanism is presented in Appendix B.

[2] We originally proposed but did not test this hypothesis in a previous review (Hagger, Wood, Stiff, & Chatzisarantis, 2009).

[3] In the pilot study we asked a small panel (N = 5) of naive participants to compare a set of three placebo solutions containing 400mg, 500mg, and 600mg of aspartame per litre of water, respectively, with an 18% glucose solution. The panel unanimously agreed that the solution containing 500mg per litre was closest in sweetness to the glucose solution. To further corroborate the panel's selection we asked a sample of undergraduate students (N = 60) to taste either the 18% glucose solution or the aspartame solution containing 500mg of aspartame per litre of water. The solutions were randomly assigned to participants using a double-blind procedure. Participants were asked to take sip of the solution and hold it in their mouth for 10-15 seconds before swallowing. They were then asked to provide ratings of sweetness, liking, consistency (thickness), strength, and palatability of the solution on 5-point scales. A series of univariate *F*-tests with Bonferroni corrections for multiple comparisons revealed no significant differences in any of the ratings (Fs < 1.54, ps > .22, $\eta_p^2 < .013$). In an additional study, we asked a second sample (N = 32) to taste both solutions, presented in a counter-balanced order and using a double-blind procedure, and identify which solution contained glucose. We also asked them to provide sweetness ratings. Chi-squared analysis revealed that the participants were unable to discern above chance which of the solutions contained glucose, $\chi^2(1) = 0.13$, $p = .714$. In addition, participants' perceptions of the sweetness of the solution did not differ

across solutions, $t(31) = 0.25$, $p = .801$, $d = 0.09$. These data provided evidence that participants' perceptions of the solutions used in the present studies on a number of taste-related criteria did not vary for the glucose and placebo solutions and that participants could not identify which solution contained glucose. The findings rule out the possibility that the effects observed in the present study were due to some implicit evaluative judgement of the solutions affecting behavior.

[4] When the data were analysed using untransformed scores the pattern of effects was identical.

[5] An alternative approach to the analysis in Study 3 was to use number of cups of the noxious drink consumed by participants as the dependent variable. Consistent with the ANOVA results, a chi-square analysis revealed that participants receiving the glucose mouth rinse consumed significantly more cups of drink than participants receiving the placebo rinse, $\chi^2(1) = 9.19$, $p = .002$.

[6] As in Study 1, when data were analysed using untransformed scores the pattern of effects was identical.

[7] For completion we conducted a focused-contrast ANOVA to confirm that time spent on the handgrip task was significantly lower among depleted participants that received the placebo mouth rinse compared to depleted participants that received the glucose mouth rinse and non-depleted participants condition regardless of mouth-rinse condition. The analysis revealed a significant contrast effect with depleted participants in the placebo condition exhibiting significantly lower handgrip task duration relative to the other groups, $F(1,40) = 15.68$, $p < .001$, $\eta^2_p = .28$.

[8] This effect was supported by a focused contrast with depleted participants assigned to the placebo mouth-rinse condition exhibiting a significantly longer response latency on the Stroop task relative to the other groups, $F(1, 36) = 11.82$, $p < .001$, $\eta^2_p = .25$.

[9] The main effect for depletion (*F*(1,35) = 11.25, *p* = .002, η_p^2 = .24) and the depletion x mouth rinse interaction effect (*F*(1,35) = 8.59, *p* = .006, η_p^2 = .20) in the reanalysis were significant and identical to the pattern of effects found in the ANOVA that excluded trait self-control. We also computed point-biserial correlations between the experimental conditions (dummy coded) and trait self-control and found no significant relationships (*r*s < .18, *p*s >.25). We concluded that, consistent with previous research (Hagger et al., 2010), the effects of trait self-control were independent of the effects of mouth-rinse and depletion conditions and their interaction.

Figure 1. Mean time spent on handgrip task adjusted for baseline handgrip strength as a function of mouth rinse condition. Placebo = condition in which participants rinsed their mouth with an artificially-sweetened (aspartame) solution; Glucose = condition in which participants rinsed their mouth with a glucose (18%) solution. Bars represent untransformed means, and lines represent standard errors.

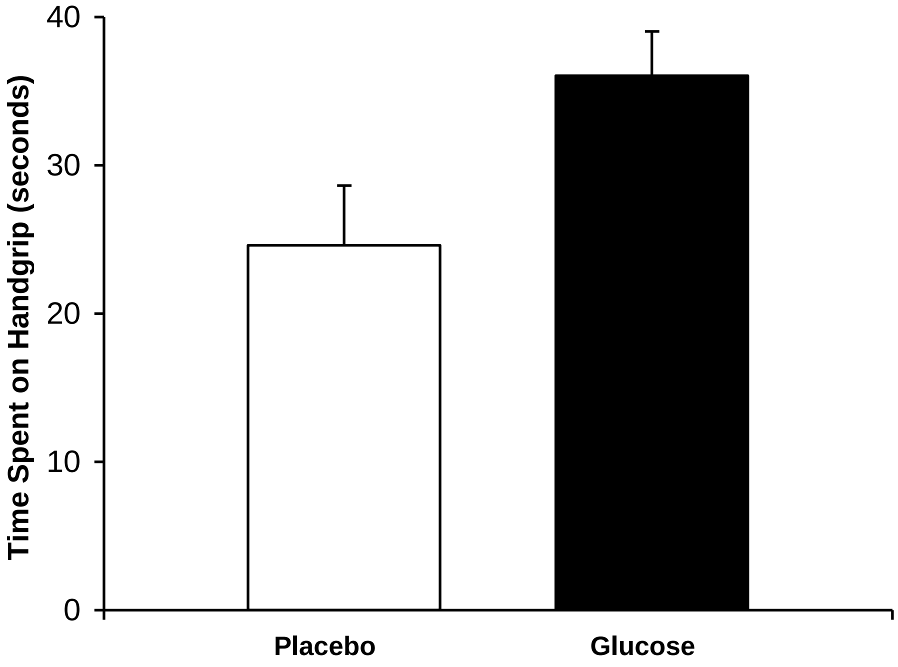

Figure 2. Mean self-control score on dependent self-control task (Study 2, primary y-axis: time spent on anagram task; Study 3, secondary y-axis: Volume of noxious drink consumed) as a function of mouth-rinse condition. Placebo = condition in which participants rinsed their mouth with an artificially-sweetened (aspartame) solution; Glucose = condition in which participants rinsed their mouth with a glucose (18%) solution. Bars represent means, and lines represent standard errors.

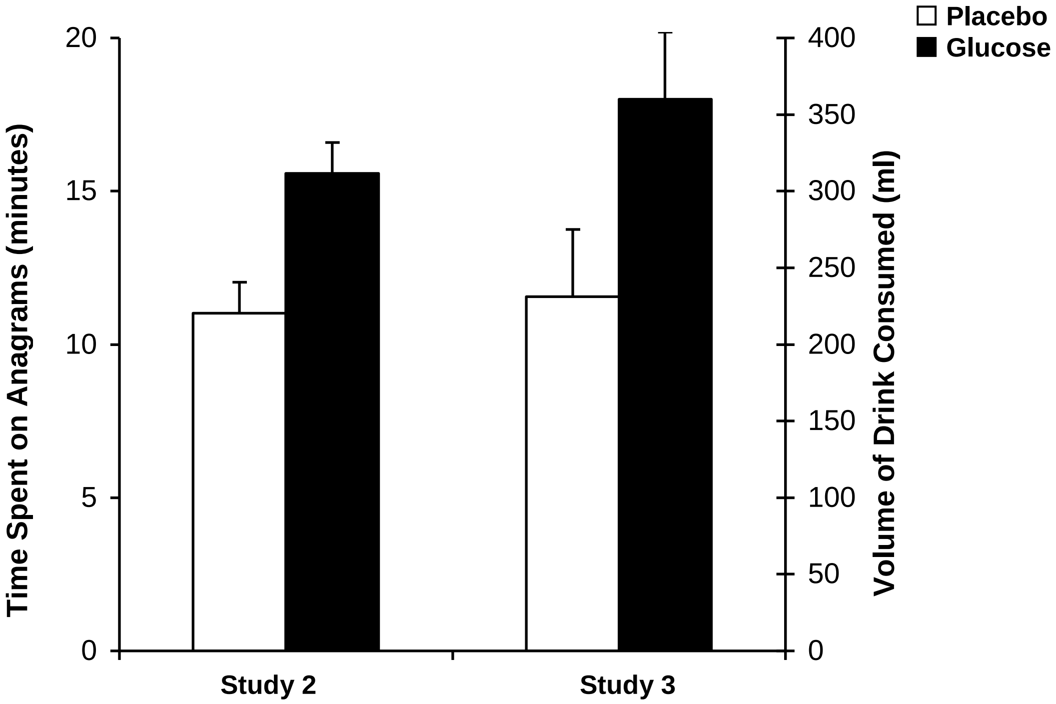

Figure 3. Mean time (seconds) spent on handgrip task adjusted for baseline hand grip strength as a function of mouth-rinse and depletion conditions. Depletion = participants engaged in an incongruent (word and text color unmatched) version of the Stroop color-naming task; no depletion = participants engaged in a congruent (word and text color matched) Stroop color-naming task; placebo = condition in which participants rinsed their mouth with an artificially-sweetened (aspartame) solution; glucose = condition in which participants rinsed their mouth with a glucose (18%) solution. Bars represent untransformed means, and lines represent standard errors.

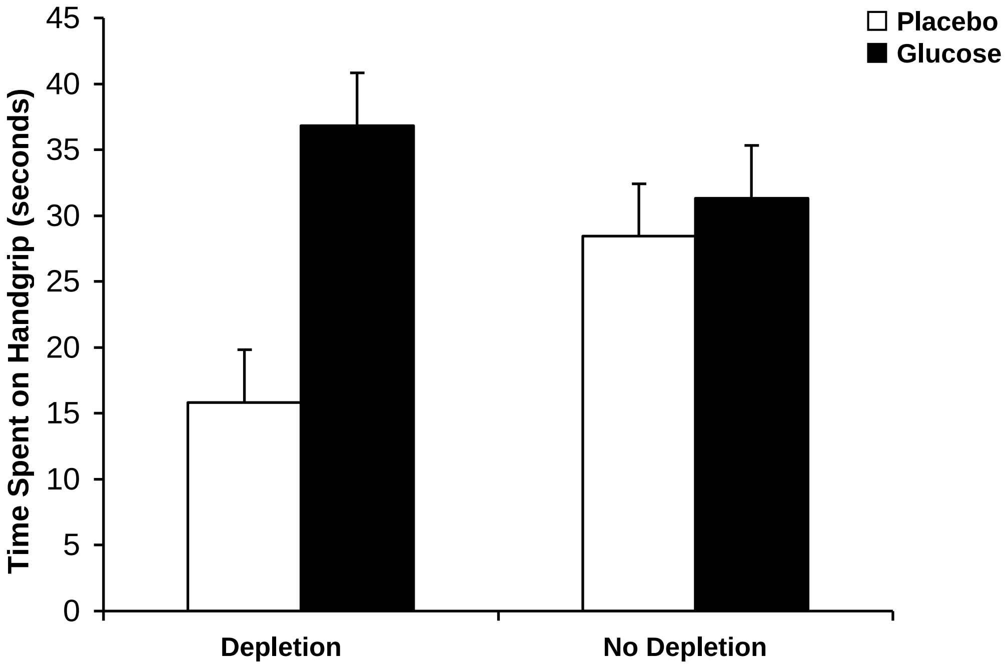

Figure 4. Mean response time (milliseconds) for incongruent trials of a Stroop color-naming task as a function of mouth-rinse and depletion conditions. Depletion = in a complex counting task with distraction; no depletion = participants engaged in a simple counting task with no distraction; placebo = condition in which participants rinsed their mouth with an artificially-sweetened (aspartame) solution; glucose = condition in which participants rinsed their mouth with a glucose (18%) solution. Bars represent means, and lines represent standard errors.