Sweet nothings:

No effects of self-control exertion on blood glucose levels

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Abstract

Prior research has suggested that circulating levels of glucose in the bloodstream help to determine success at self-control. However, this idea has been challenged on multiple grounds. The current research added new evidence to the debate by testing 1) the extent to which exercising self-control reduces blood glucose levels, 2) whether consuming glucose, rinsing the mouth with glucose, or consuming aspartame (a sugar substitute) increases blood glucose levels, and 3) the extent to which measured blood glucose levels relate to emotional responding, delay discounting, and cognitive control, respectively. We found no evidence that blood glucose levels influence or are influenced by self-control.

Key words: Ego depletion, self-control, resource model, glucose, aspartame

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A foundational idea in scholarship on willpower is that the capacity to control one's responses relies on a limited inner resource or strength (Muraven & Baumeister, 2000). The primary evidence to support this idea comes from experiments in which participants performed two self-control tasks in succession. The key finding is that performing self-control at Time 1 reduces success at self-control at Time 2, compared to not performing self-control at Time 1 (see Baumeister, Tice, & Vohs, 2007; Hagger Wood, Stiff, & Chatzisarantis, 2010). This temporary impairment of self-control is known as the *ego depletion effect*, and it is congruent with the idea that exercising willpower relies on some limited inner resource that becomes depleted with use.

Some evidence has suggested a physiological basis for the limited resource, namely glucose in the bloodstream. An influential series of studies found that self-control reduces circulating levels of glucose in the bloodstream compared to performing similar tasks that do not require self-control (Gailliot et al., 2007). Further, those studies found that blood glucose levels correlate with self-control performance, and that putting glucose back into the system (by having participants consume glucose-laden beverages) restores success at self-control. Together, the three strands of evidence reported by Gailliot et al.—drops in glucose after self-control exertion, measured glucose levels predicting subsequent self-control performance, and adding glucose to the bloodstream eliminating the depletion effect—strongly implicated glucose as a physiological factor in successful self-control.

But those ideas have drawn intense scrutiny and skepticism. Both the ego depletion effect and the purported role of glucose in self-control have been challenged on multiple grounds. Although an initial meta-analysis found robust evidence for a medium-to-large sized ego depletion effect (Hagger et al., 2010), a subsequent meta-analysis used regression-based

correction techniques to account for publication bias and reduced the estimate for the ego depletion effect down to a zero or null effect (Carter, Kofler, Forster, & McCullough, 2015). However, those bias correction techniques have themselves been challenged, with evidence suggesting that they underestimate true effect sizes especially when drawing from studies with small samples and high heterogeneity in effect sizes (Dang, 2018; Inzlicht, Gervais, & Berkman, 2015; Moreno et al., 2009; Reed, 2015; Simonsohn, 2017)—characteristics that exist in the ego depletion literature. More recently, a multisite replication study found a null effect of ego depletion (Hagger et al., 2016), and other preregistered studies have found significant but smaller than anticipated ego depletion effects (Garrison, Finley, & Schmeichel, *in press*; Dang, Liu, Liu, & Mao, 2017; cf. Lurquin et al., 2016). Therefore, the empirical status of the ego depletion effect is less certain than it appeared to be in the original meta-analysis of the effect.

Similarly, the purported role of glucose in self-control has been challenged both in terms of its physiological plausibility (Kurzban, 2010) and by evidence suggesting that merely swishing glucose in the mouth mimics the effects of glucose ingestion (Molden et al., 2012; Sanders et al., 2012; Carter & McCullough, 2013; Hagger & Chatzisarantis, 2013; cf. Boyle et al., 2016; Dang, 2016). Additionally, whereas some researchers have found, like Gailliot et al. (2007), a drop in blood glucose levels after self-control exertion (Dvorak & Simons, 2009; see also Fairclough & Houston, 2004), others have failed to find such an effect (Marcora, Staiano, & Manning, 2009; Molden et al., 2012) or have found mixed results depending on how blood glucose was measured (Boyle et al., 2016). A recent meta-analysis found little evidence to support glucose as the underlying resource in self-control, although the meta-analysis included only 15 studies, with most studies testing small samples (Dang, 2016; see also Vadillo, Gold, & Osman, 2016). Thus, compared to the behavioral evidence regarding ego depletion, both the

effects of exercising self-control on blood glucose levels and the relationship between blood glucose levels and subsequent self-control have received less attention.

The current experiment tested the hypothesis that exercising self-control reduces blood glucose levels. We tested three times as many participants as the most relevant previous study (Dvorak & Simons, 2009), which afforded us greater statistical power than previous studies to detect potentially small effects. We also assessed blood glucose levels after consuming glucose, rinsing the mouth with glucose, or consuming aspartame (a sugar substitute). Then we explored the extent to which measured blood glucose levels relate to delay discount rates, subjective responses to emotional images, and cognitive control as measured by a flanker interference task. (Two of these measures—the delay discounting task and the flanker task—may be associated with self-control; we also measured subjective responses to emotional images to explore potential emotional consequences of glucose consumption.) Below we report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study.

Method

Participants. We initially aimed to collect data from 150 participants per depletion condition for a total of 300 participants, and we calculated that this sample size would provide us 80% power to detect an effect of $d = 0.32$ of the depletion condition on blood glucose levels and 80% power to detect a correlation of $|\rho| = 0.14$ between blood glucose levels and other dependent measures. To account for exclusions and other errors, we intended to oversample by stopping at the end of the semester in which we passed the target of 300 participants. After 6 semesters, a total of 371 undergraduate students (133 men, 212 women, 26 unreported; age $M = 18.70$, $SD = 1.80$) completed a laboratory experiment investigating the effects of sweeteners and sugar on mental functions and received credit toward a course requirement.

To reduce variability in blood glucose levels we instructed all participants to refrain from eating for 4 hours before the experiment. We checked compliance by asking participants when they last ate. Ninety-one participants reported noncompliance. We therefore conducted analyses with and without how long it had been since participants last ate as a covariate ($M = 7.27$ hours, $SD = 4.79$). Below we use footnotes to indicate when including the covariate altered the results. For simplicity, we report analyses in the main manuscript without the covariate, and report the same analyses with the covariate in the supplemental materials. Forty-nine additional students participated in the study but were excluded from analyses for the following reasons: 8 were outliers (more than 3 SD s from the sample mean) on at least one blood glucose assessment, 9 reported being diabetic, 5 did not finish all procedures, 4 did not follow drink instructions (i.e., swallowed after swishing, opted not to drink full beverage), 12 did not follow instructions on the writing task (see below), 4 had missing data due to computer issues, and 7 encountered experimenter error (i.e., 1 missing condition information, 6 completed procedures out of order).

Procedure and materials. Participants were randomly assigned to condition in a 2 (Writing Task: free writing vs. controlled writing) x 3 (Drink: glucose ingest, aspartame ingest, glucose swish) between-subjects design. All experimental materials are available online. Figure 1 displays the order of the experimental tasks. Participants completed the study individually in a small psychology laboratory room with a desk and single computer. After providing informed consent participants completed several self-report measures on a computer, including a demographics questionnaire, BIS/BAS scales (Carver & White, 1994), handedness inventory, Positive and Negative Affect Schedules (Watson & Clark, 1999), and Barratt Impulsiveness Scale (Patton, Stanford, & Barratt, 1995).¹ Next, the experimenter collected a baseline blood

¹ These self-report measures were included for exploratory purposes and are not included in the following analyses. All data will be made available in an online supplement upon publication.

glucose assessment (T1) as described below.

Writing task. After the first blood glucose assessment participants spent 6 minutes writing a story about a recent trip they had taken on a blank sheet of paper. Participants in the *free writing condition* ($n = 185$) simply wrote as they pleased. Those in the *controlled writing condition* ($n = 186$) were instructed not to use the letters *a* or *n* anywhere in the story. This manipulation has been used previously to induce ego depletion (e.g., Schmeichel, 2007; Garrison, Finley, & Schmeichel, in press). To ensure the experimenter remained blind to experimental condition, participants received the writing task in an envelope and were instructed to place the papers back in the envelope when time expired. Immediately after the writing task the experimenter took a post-task blood glucose assessment (T2) to test the effect of the writing manipulation on glucose levels.

Drink manipulation. After the second blood glucose assessment all participants sampled a drink that “may contain sugar or sweetener.” Participants received either a glucose or an aspartame solution. Those in the *glucose ingest condition* ($n = 125$) received 36g of sugar in a 400 mL solution (9% concentration) to consume. Participants in the *glucose swish condition* ($n = 128$) received 25 mL of the same solution to rinse in their mouths and spit out after 5 seconds. Those in the *aspartame condition* ($n = 118$) received a taste-matched aspartame solution (8g of aspartame in a 400 mL solution; 2% concentration) to consume.²

Participants then indicated on the computer whether they liked the drink (*yes* or *no*), if they thought the drink included sweetener (*yes* or *no*), the approximate concentration of the sweetener (0-30%), and the type of sweetener used (sugar or Equal). To allow any glucose to metabolize, participants spent the next 10 min filling out additional questionnaires on the

² Taste matching was confirmed in a pilot test conducted among a small sample of undergraduate students prior to beginning the study.

computer, including the Trait Self-Control Scale (Tangney, Baumeister, & Boone, 2004), Approach Avoidance Temperament Questionnaire (Elliot & Thrash, 2010), and Berkeley Expressivity Scale (Gross & Oliver, 1995).³ Another blood glucose assessment (T3) was taken following the 10 min questionnaire period to check the success of the drink manipulation in altering glucose levels and to correlate with other dependent measures.

Then participants completed three other dependent measures on the computer—a passive picture viewing task, a delay discounting task, and a cognitive control task (i.e., a flanker task). We included this trio of additional dependent measures to assess the extent to which they were influenced by blood glucose levels. Two of the tasks, namely the flanker task and the delay discounting task, are thought to relate to self-control. The picture viewing task was included to explore the extent to which glucose influences emotional reactivity. Emotional reactivity may be relevant for self-control as described by some models (e.g., Inzlicht & Schmeichel, 2012) but does not directly tap controlled processing.

The order of the dependent measures varied such that participants viewed pictures or completed the delay discounting task in counterbalanced order (to avoid potential order effects on these two tasks), before completing the flanker task which was always last. We placed the flanker task at the end of the session because it requires sustained attentional control (similar to the Stroop task), which may induce further depletion or frustration, and we did not want the experience of performing the flanker task to influence the other measures.

Picture viewing. Participants viewed 57 pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1990). Positive, negative, and neutral pictures appeared onscreen for 6000 ms in three blocks of 19 pictures each. Approximately equal

³ These self-report measures were included as filler questionnaires as well as for exploratory purposes and are not included in the following analyses. All data will be made available in an online supplement upon publication.

numbers of appetitive (e.g., desserts, erotica) aversive (e.g., attackers with weapons, injuries) and neutral pictures (e.g., buildings, neutral faces) appeared in each block. Following each picture, participants saw self-assessment manikins prompting them to report their current emotional valence (from 1 = *not happy* to 7 = *happy*) and arousal (from 1 = *calm* to 7 = *excited*). The picture viewing task lasted approximately 9 minutes. To assess potential changes in emotional responding after glucose ingestion and self-control exertion, we scored responses such that larger values indicate more intense emotional responses.

Delay discounting task. Participants chose between pairs of hypothetical monetary rewards in 22 trials split into two types (Weber et al., 2007). In *delay trials*, participants chose between receiving \$50 immediately versus receiving other dollar amounts in three months, with values ranging from \$50 to \$100 in increments of \$5. In *acceleration trials*, participants chose between receiving \$75 in three months versus receiving 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. The delay discounting task lasted approximately 2 minutes. We rescored both delay and accelerate interference points as z-scores, transformed such that larger numbers indicate a willingness to wait longer for a reward.

Flanker task. Last, participants completed a version of the flanker task (Eriksen & Eriksen, 1974) that depicted left-facing 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. Inter-trial 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. The experimental trials portion of the flanker task lasted approximately 7 minutes. After completing the flanker task, participants were debriefed and thanked for their participation. We scored flanker performance as the proportion of correct responses to all trials (i.e., accuracy) as well as flanker interference scores, calculated by subtracting RTs to correct congruent trials from RTs to correct incongruent trials.

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 them with an Accu-Chek Aviva glucose monitor. Participants rubbed their fingers together to facilitate blood flow, and then the experimenter cleaned the finger with an alcohol pad before using the lancet to prick the fingertip. Participants used a different finger on their non-dominant hand for each blood glucose assessment. The experimenter applied pressure to get a blood sample and analyzed 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.

The first measure of blood glucose served as a baseline (T1), the second measure was used to test the effects of the writing manipulation on blood glucose levels (T2), and the third

measure was to verify the effectiveness of the drink manipulation (T3) and to relate to subsequent task performance and responding. The analyses examining change in blood glucose over time include only the 321 participants who supplied blood on all three glucose assessments; the other analyses vary slightly in sample size due to missing data or participant error.

Results

We analyzed changes in blood glucose using a repeated measures ANOVA. We then explored the other dependent measures in a MANOVA with responses scored so that higher numbers indicate less controlled responding (i.e., more emotion, more impulsive choices, more errors), as described below. Last, we tested the correlations between blood glucose levels after the drink manipulation (T3) and the dependent measures of task performance. Table 1 displays blood glucose means and standard deviations by condition, and Table 2 displays the rescored dependent measures means and standard deviations by conditions. Raw dependent measure descriptive statistics are reported in the supplemental materials. We set alpha at 0.05 for all hypothesis tests.

Blood glucose. First we examined changes in blood glucose levels in a 3 (Time) $\times$ 2 (Writing Condition: free vs controlled writing) $\times$ 3 (Drink Condition: glucose ingest, glucose swish, aspartame ingest) mixed ANOVA. When the assumption of sphericity was violated we applied the Greenhouse-Geisser correction. We found a within-subjects effect of time, $F(1.70, 535.66) = 70.91, p < .001, \text{partial } \eta^2 = .184$, and a between-subjects effect of drink condition, $F(2, 315) = 3.51, p = .031, \text{partial } \eta^2 = .022$. These main effects were qualified by an assessment time by drink condition interaction, $F(3.40, 535.66) = 26.53, p < .001, \text{partial } \eta^2 = .144$.

As depicted in Figure 2, the writing manipulation had no effect on blood glucose levels (from T1 to T2). Both the glucose drink and the aspartame drink increased blood glucose levels

(from T2 to T3), whereas blood glucose levels showed a non-significant decrease over time in the glucose swish condition. To examine the effect of drink condition, we ran follow-up ANOVAs at each time point. We found no effect of drink condition at baseline (T1) nor after the writing task (T2), $ps > .320$. After the drink manipulation (T3) we found a significant effect, $F(2, 318) = 19.25, p < .001, partial \eta^2 = .108$. Follow-up pairwise comparisons revealed significant differences among all three drink conditions, $ps < .004$, such that the glucose drink induced the highest blood glucose levels, $M = 107.04, 95\% \text{ CI } [104.44, 109.63]$, glucose swish produced the lowest blood glucose levels, $M = 95.50, 95\% \text{ CI } [92.91, 98.08]$, with the aspartame drink falling in between, $M = 100.93, 95\% \text{ CI } [98.29, 103.58]$.

Task dependent measures. We scored the dependent measures so that higher numerical values reflect less controlled responding. Specifically, we recoded valence scores across all images as absolute differences from the neutral midpoint (higher numbers indicate more extreme emotional valence) and converted the delay discounting accelerate and delay scores into z-scores and multiplied the resulting acceleration scores by -1 (so that higher z-scores indicate more impulsive behaviors). Error rates and interference scores from the flanker task were left unchanged (higher numbers indicate poorer control), and arousal ratings were also left unchanged (higher numbers indicate higher arousal). We entered these dependent measures into a 2 (Writing Condition: free vs controlled writing) $\times$ 3 (Drink Condition: glucose ingest, glucose swish, aspartame ingest) MANOVA and followed up any significant multivariate findings with univariate tests.

We found only a significant multivariate effect of drink condition, $F(12, 696) = 2.12, p = .014, partial \eta^2 = .035$. Follow-up univariate tests revealed an effect of drink condition on the delay score, $F(2, 352) = 3.25, p = .040, partial \eta^2 = .018$, and on flanker interference, $F(2, 352)$

$= 3.02, p = .050, \text{partial } \eta^2 = .017$. Participants in the aspartame condition responded less impulsively ($M = -0.17, 95\% \text{ CI } [-0.35, 0.02, 109.63]$) on the delay discounting tasks compared to participants in the glucose swish condition, ($M = 0.17, 95\% \text{ CI } [-0.01, 0.34]$), $p = .011$, with participants in the glucose drink condition ($M = 0.02, 95\% \text{ CI } [-0.16, 0.20]$) not significantly different from the other groups. And participants in the glucose swish condition ($M = 128.56, 95\% \text{ CI } [120.29, 136.82]$) exhibited less flanker interference compared to participants in the glucose drink condition, ($M = 143.01, 95\% \text{ CI } [134.61, 151.41]$), $p = .016$, with participants in the aspartame drink condition ($M = 138.14, 95\% \text{ CI } [129.41, 146.87]$) not significantly different from the other groups.⁴

Task dependent measures and blood glucose levels. To examine the relationship between blood glucose levels and subsequent responding, we correlated the final blood glucose measure (post drink manipulation; T3) with the dependent measures. Negative correlations indicate that higher blood glucose levels related to more controlled responding (i.e., less extreme emotional responses, less delay discounting, and fewer errors and faster reaction times). As shown in Table 3, we found no significant correlations between blood glucose levels at T3 and any of the subsequent dependent measures.

⁴ Including time since last ate as a covariate resulted in a significant multivariate effect of drink condition, $F(12, 664) = 2.39, p = .005, \text{partial } \eta^2 = .041$, and a drink condition by depletion condition interaction, $F(12, 664) = 1.82, p = .042, \text{partial } \eta^2 = .032$. The significant univariate effects of drink condition on delay scores and flanker interference remained significant when the covariate was included. As reported in the supplemental materials, follow-up ANOVAs also revealed a significant univariate effect of drink condition on arousal, $F(2, 336) = 3.11, p = .046, \text{partial } \eta^2 = .018$, delay scores, $F(2, 336) = 3.59, p = .029, \text{partial } \eta^2 = .021$, and interference scores, $F(2, 336) = 3.66, p = .027, \text{partial } \eta^2 = .021$, such that participants in the glucose swish condition reported the highest arousal ($M = 4.11, 95\% \text{ CI } [3.97, 4.24]$), aspartame drink the lowest arousal ($M = 3.88, 95\% \text{ CI } [3.75, 4.02]$), and glucose drink in between ($M = 3.92, 95\% \text{ CI } [3.78, 4.05]$). For the drink by depletion interaction, the follow-up between-subjects ANOVA found only a significant effect on arousal, $F(2, 336) = 3.15, p = .044, \text{partial } \eta^2 = .018$, such that depleted participants who swished glucose reported the highest levels of arousal during the picture viewing task, whereas depleted participants in the aspartame drink condition reported the lowest arousal. All other results remained unchanged. See supplemental materials for more information.

Discussion

The purpose of this study was threefold. First, we tested the hypothesis that exercising self-control (compared to not exercising self-control) reduces blood glucose levels. Second, we wanted to verify that consuming a sugary drink (relative to consuming a sugar substitute or mouth-rinsing with a sugar solution) increases blood glucose levels. And third, we tested the hypothesis that blood glucose levels correlate with subsequent responding.

Exercising self-control did not reduce blood glucose levels. We observed similar blood glucose levels in participants who had completed a controlled writing task compared to participants who had performed a similar task that did not require self-control. The current experiment had ample power to detect small effects of the writing manipulation on blood glucose levels (because we collected more data than indicated by our original power analysis, we had 80% power to detect an effect of $d = 0.31$ of the writing condition on blood glucose levels), and combined with other studies that also found non-significant changes in blood glucose levels following the exercise of self-control (Marcora et al., 2009; Molden et al., 2012; see also Dang, 2016), the evidence suggests that glucose levels in the bloodstream are not appreciably altered by exercising self-control.

However, the current study does not warrant a definitive conclusion regarding the relationship between self-control and blood glucose levels. It is possible that the writing manipulation used in the current study was not sufficiently strong to yield changes in blood glucose levels, or perhaps the measure of blood glucose levels was not precise enough to detect such an effect. Perhaps longer or more challenging self-control manipulations or more precise blood glucose measurements would cause changes in blood glucose levels. The current results cast doubt on the plausibility of such predictions.

Consuming a sugary drink increased blood glucose levels, as expected. However, we also found that consuming a drink made with a sugar substitute (i.e., aspartame) increased blood glucose levels. We had not expected this result, and past research examining the metabolic effects of consuming aspartame and other sugar substitutes features mainly small sample sizes and reports mixed results (e.g., Melanson, Westerterp-Plantenga, Campfield, & Saris, 1999; see also Romo-Romo et al., 2016). In the present context, the possibility that consuming sugar substitutes increases blood glucose levels is important because in several prior experiments consuming glucose has been found to undo the ego depletion effect compared to consuming a sugar substitute. However, in very few of those experiments has blood glucose been measured to verify that drink manipulations differentially influence blood glucose levels. The results of the current experiment suggest that consuming aspartame increases blood glucose levels, although not as much as does consuming sugar. Rinsing the mouth with a glucose drink did not change blood glucose levels in the current experiment, as expected.

Additionally, blood glucose levels did not relate to any of the dependent measures in this experiment. Hence, unlike some past research that found correlations between blood glucose levels and measures of controlled processing, such as Stroop performance (Gailliot et al., 2007), persistence on anagrams (Dvorak & Simons, 2009), and delay discounting (Wang & Dvorak, 2010), in the current study blood glucose levels did not relate to delay discounting, emotional responding to pictures, or performance on a cognitive control task (i.e., the flanker task).

Taken together, the current findings argue against the idea that glucose functions as biological basis of the hypothetical resource underlying self-control (assuming that such a resource exists). By extension, the current results also do not fit with theories that posit that ego

depletion stems from the conservation of glucose as a mental resource (Beedie & Lane, 2012); conservation is not necessary if the hypothesized resource is not susceptible to depletion.

Limitations

The current study is limited by the fact that we did not observe an ego depletion effect (i.e., changes in behavior/performance). To be sure, testing the ego depletion effect was not the primary aim of the experiment. At the time of study initiation (in the fall of 2013), the first two dependent measures in this experiment (i.e., emotional reactions to pictures and delay discounting) had not been used in the depletion literature and were therefore considered exploratory measures.⁵ Moreover, the most traditional dependent measure for testing the ego depletion effect, namely flanker task performance, was administered approximately twenty minutes after depletion manipulation, which likely reduced our ability to find a depletion effect. In most ego depletion studies the dependent measure is assessed moments after the depletion manipulation. These design features may help to account for the non-significant overall main effect of depletion condition.

It is also possible that the depletion manipulation we used in the current experiment was too weak or not sufficient to drain the self-control resource (although other studies have found significant depletion effects using the same writing task manipulation; e.g., Garrison, Finley, & Schmeichel, in press). If that were the case, then we would expect to see (and in fact did see) no changes in blood glucose nor subsequent responding (particularly on the flanker task) as a function of the writing manipulation. We cannot rule out this possibility without further research.

⁵ Subsequent work has found that exercising self-control may influence emotional reactions to pictures depending on individual differences in extraversion and approach motivation (e.g., Finley & Schmeichel, in press), and some recent evidence has linked depletion to delay discounting; Aranovich, McClure, Fryer, & Mathalon, 2018; Bayer & Yamima, 2018; cf. Heckman et al., 2017).

It is also possible, as skeptics have claimed, that exercising self-control does not influence subsequent responding (i.e., no ego depletion effect; Carter et al., 2015). As mentioned above, the primary aim of the current experiment was not to test the ego depletion effect. Rather, the primary aim was to test the effects of exercising self-control on blood glucose levels. Indeed, the most relevant dependent measure for assessing the ego depletion effect (i.e., flanker task performance) occurred much later (approximately 20 minutes) after the depletion manipulation than is typical in most ego depletion studies. Still, if we had found reduced flanker performance, then this would have been consistent with the ego depletion effect. We did not find reduced flanker performance, which is at best an ambiguous outcome, due either to the fact that the ego depletion effect does not exist or, as we have suggested, due to the fact that the current study was not adequate to detect it (nor was it designed to).

Despite these limitations, it is nonetheless true that we found no evidence that blood glucose levels related to subsequent responding. Indeed, we found no significant correlations between blood glucose levels at T3 and any subsequent dependent measure, even though we had 80% power to detect correlations as small as $|r| = 0.14$. Even if the depletion manipulation did not drain the self-control resource, if glucose does underlie self-control then we would expect to find significant correlations between blood glucose levels and subsequent responding (especially delay discounting and flanker performance), but we found none.

Conclusions

The current study examined the links between blood glucose levels and self-control. We found no evidence to suggest that exercising self-control reduces blood glucose levels, nor did we find evidence to suggest that blood glucose levels correlate with subsequent responding. If the hypothesized resource for self-control exists, then the current results cast doubt on the

possibility that glucose serves as its physiological basis (see also Kurzban, 2010; Vadillo et al., 2016). Unexpectedly, we found that aspartame ingestion increased blood glucose levels, although glucose ingestion increased blood glucose levels even more. Future research is needed to test the effects of non-caloric sweeteners on blood glucose levels and other downstream effects.

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Table 1: Blood glucose descriptive statistics by condition, means (standard deviations)

	Free Writing Condition			Controlled Writing Condition		
	Glucose Drink (<i>n</i> = 61)	Glucose Swish (<i>n</i> = 65)	Aspartame (<i>n</i> = 59)	Glucose Drink (<i>n</i> = 64)	Glucose Swish (<i>n</i> = 63)	Aspartame (<i>n</i> = 59)
Sample size with all BG measures	<i>n</i> = 52	<i>n</i> = 56	<i>n</i> = 49	<i>n</i> = 56	<i>n</i> = 53	<i>n</i> = 55
Resting (T1)	96.92 (11.95)	97.38 (12.51)	96.08 (11.58)	96.93 (12.66)	95.38 (12.16)	96.24 (12.64)
After Writing Task (T2)	95.46 (10.62)	97.38 (13.96)	93.35 (9.44)	96.11 (12.00)	94.38 (12.57)	94.22 (13.15)
After Drink Manipulation (T3)	106.62 (11.85)	96.05 (12.57)	101.53 (13.01)	107.43 (14.36)	94.91 (14.49)	100.40 (15.76)

Table 2: Dependent measure descriptive statistics (*Ms* and *SDs*) by condition. Dependent measure values scored so that higher values indicate more emotion and less controlled responding.

	Free Writing Condition			Controlled Writing Condition		
	Glucose Drink	Glucose Swish	Aspartame	Glucose Drink	Glucose Swish	Aspartame
Image Ratings	<i>n</i> = 61	<i>n</i> = 65	<i>n</i> = 59	<i>n</i> = 63	<i>n</i> = 63	<i>n</i> = 59
Valence (deviance from neutral)	1.26 (0.42)	1.27 (0.38)	1.24 (0.35)	1.33 (0.36)	1.27 (0.39)	1.34 (0.38)
Arousal	3.88 (0.67)	3.91 (0.71)	4.00 (0.77)	3.97 (0.76)	4.22 (0.72)	3.79 (0.73)
Delay Discounting	<i>n</i> = 61	<i>n</i> = 64	<i>n</i> = 58	<i>n</i> = 63	<i>n</i> = 63	<i>n</i> = 58
Accelerate (reversed z-score)	0.10 (1.06)	-0.09 (0.97)	-0.01 (0.96)	-0.02 (0.95)	0.20 (1.12)	-0.19 (0.90)
Delay (z-score)	0.08 (1.05)	0.03 (1.02)	-0.11 (0.89)	-0.07 (0.97)	0.28 (1.11)	-0.24 (0.89)
Flanker	<i>n</i> = 60	<i>n</i> = 64	<i>n</i> = 57	<i>n</i> = 62	<i>n</i> = 62	<i>n</i> = 58
Error Rate	0.112 (0.133)	0.106 (0.095)	0.091 (0.056)	0.101 (0.112)	0.085 (0.050)	0.087 (0.039)
Interference	146.16 (44.01)	124.93 (51.53)	132.74 (45.80)	140.26 (42.42)	132.18 (49.68)	142.43 (46.80)

Note: *Ns* vary due to missing data or participant error

Table 3: Correlations between post-drink (T3) blood glucose levels and subsequent DVs (rescored so that higher values relate to more emotion and less controlled responding) collapsed across all conditions.

Image Ratings	<i>n</i> = 321
Valence (deviance from neutral)	.080
Arousal	-.018
Delay Discounting	<i>n</i> = 319
Accelerate (reversed z-score)	-.044
Delay(z-score)	-.051
Flanker	<i>n</i> = 313
Error Rate	.017
Interference	.090

Note: Sample sizes vary across measures due to some participants missing data because of equipment or computer error, or because participants pressed the wrong keys resulting in no recorded responses.

Figure 1: Order of procedures. Participants swished glucose or consumed glucose or aspartame during the drink manipulation (third box from left). Blood glucose assessments taken at T1, T2, and T3 are depicted as drops.

Figure 2: Changes in blood glucose over time by writing condition and drink condition.

Writing condition had no effect on blood glucose levels.