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No Effects of Ingesting or Rinsing Sucrose on Depleted Self-Control Performance

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Abstract

Self-control tasks appear to deplete a limited resource resulting in reduced subsequent self-control performance; a state of ego depletion. Evidence of reduced peripheral glucose by exertion of self-control, and attenuation of ego depletion by carbohydrate metabolism underpins the proposition that this macronutrient provides the energetic source of self-control. However, the demonstration of positive, non-metabolic effects on ego depletion when merely sensing carbohydrates orally contradicts this hypothesis. Recent studies have also failed to support both metabolic and non-metabolic accounts. The effects of ingesting or rinsing a carbohydrate (sucrose) and an artificially sweetened (sucralose) solution on capillary blood and interstitial glucose, and depleted self-control performance were examined in older adults. Forty, healthy, adults (50–65 years) ingested and rinsed sucrose and sucralose solutions in a 2(method) x 2(source), fully counterbalanced, repeated measures, crossover design. Capillary blood and interstitial glucose responses were assayed. Depleted self-control performance (induced by the Bakan visual processing task) on an attention switch task was assessed under each study condition. Ego depletion had no consistent effects on peripheral glucose levels and no significant effects of ingesting or rinsing sucrose on self-control were observed. The act of rinsing the solutions, independent of energetic content, resulted in a small, non-significant enhancement of performance on the attention switch task relative to ingesting the same solutions (RT: $p = .05$; accuracy: $p = .09$). In conclusion, a metabolic account of self-control was not supported. Whilst a positive effect of rinsing on depleted self-control performance was demonstrated, this was independent of energetic content. Findings suggest glucose is an unlikely physiological analogue for self-control resources.

The Effect of Ingesting and Rinsing Sucrose and Sucralose on Depleted Self-Control Performance

Acts of self-control require the effortful inhibition of predominant responses, emotions, thoughts, and impulses, permitting behaviour to vary adaptively moment to moment [1, 2]. Exertion of self-control is considered to be a key process in the human personality structure as flexibility in behavioural response permits the attainment of goals, and facilitates adherence to rules, laws, and social norms and standards [3]. Indeed, self-control capacity has been positively associated with an impressive array of behaviours of personal and societal significance (e.g., reduced aggression [4]; scholistic achievement [5]; interpersonal success [6]; criminality [7]).

The capacity to exert self-control appears to be limited [8]. The resource strength model maintains that acts of self-control consume and temporarily deplete a common, and crucially limited, resource; ultimately resulting in 'ego depletion' [9, 10]. Self-control performance is therefore determined by the current strength or level of depletion of this common resource. Indeed, initial expenditure of self-control has been repeatedly demonstrated to result in reduced subsequent performance on self-control tasks independent of differing task modalities [11]. This would fit with the claim that the resource involved in inhibition and self-control reflects a form of executive function [12, 13].

Gailliot and Baumeister [14] extended the strength model from the metaphorical to the physical by proposing that glucose is the central energy source of self-control. This proposition was founded on evidence of (i) reduced blood glucose levels after initial exertion of self-control; (ii) an association between subsequent, post-depletion, self-control performance and blood glucose decline, and (iii) attenuation of the detrimental ego depletion effect on self-control performance after ingestion of glucose, but not artificial sweetener (sucralose) [14]. Subsequent attempts to replicate the moderation of peripheral blood glucose by exertion of self-control have not supported this original finding [15]. The amount of glucose required for acts of self-control is likely to be negligible in absolute brain energy cost terms. Furthermore, reduced peripheral glucose is unlikely considering the efficiency of homeostatic systems in maintaining brain energy levels [16].

The capacity of glucose ingestion to counteract the impairing effect of ego depletion has however been replicated [17, 18, 19, 20]. Nevertheless, the precise role of glucose in self-control performance remains indistinct. Firstly, a number of studies have demonstrated that glucose can influence performance on self-control tasks in a non-energetic manner. Merely sensing carbohydrates in the oral cavity can confer a restorative benefit on cognitive self-control performance under conditions of ego depletion [21, 15, 22]. The positive effect of carbohydrate oral rinsing has also been demonstrated in physical endurance performance [23, 24], conferring greater performance benefits than ingestion [25]. Such findings suggest a potential motivational rather than metabolic effect of carbohydrates on performance, underpinned by activation of motivational neural reward pathways [24, 26, 15]. Ego depletion effects can also be moderated by manipulation of subjective states such as motivation [27], expectation of self-control capacity [28], and self-affirmation [29]. Evidence of moderation of self-control performance by subjective state casts further doubts on the specific role of glucose.

The existing evidence for metabolic accounts of self-control (e.g., [14, 11] has also received criticism on the statistical grounds of potentially inflated effect sizes and methodological shortcomings [16, 30, 31, 32]. Further, failed attempts to replicate the effects of carbohydrate ingestion and oral sensing suggest the effect of carbohydrate on self-control performance may not be as robust as the literature suggests [30, 31]. In sum, whilst the ingestion and rinsing of carbohydrate-containing solutions have previously been shown to attenuate the ego depletion effect, critiques of the existing evidence, and recent failures to replicate the effect, necessitate further independent examination of the relationship between carbohydrate and self-control.

The present study examined the effect of ingesting and rinsing a sucrose and sucralose solution on a self-control task under conditions of ego depletion. The potential depletion of glucose by the exertion of self-control, and moderation of self-control by the metabolism of glucose, were rigorously assessed using formal laboratory standard capillary blood glucose analysis techniques and continuous interstitial glucose monitoring. Previous studies examining the effects of glucose ingesting and rinsing on self-control have recruited young, predominantly student samples. The facilitative effects of carbohydrate intake on cognitive performance may be more potent in individuals with disrupted metabolic or cognitive functioning [33, 34, 35, 36, 37] rather than young, high functioning students. Indeed, glucose

administration has been shown to selectively enhance cognitive performance in elderly, but not the young [33, 34] and was additionally mediated by glucoregulatory control in older but not younger adults [33]. Ageing is associated with cognitive decline and disturbed regulation of primary hormones and neurotransmitters mediating glucose regulation and cognitive function (e.g., acetylcholine, adrenaline [37]). Therefore, older adults were considered a highly relevant population in which to study the effects of ingesting and rinsing carbohydrate solutions on self-control performance, due to commonly observed age-related decline in cognitive control [38] and an age-associated deterioration in glucose regulation [37].

Methods

Design

A 2 (method: rinse or ingest) X 2 (source: sucrose or sucralose) fully counterbalanced (William's Latin Square), within subjects, crossover design was employed to expose participants to each experimental condition. Participants were required to ingest or orally rinse sucrose and sucralose solutions (sucrose/ingest; sucrose/rinse; sucralose/ingest; sucralose/rinse) over four study visits separated by one week. At each visit, self-control was depleted prior to solution intake and performance on a different task requiring self-control was assessed post-intake. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human participants were approved by the University of Leeds' School of Psychology Research Ethics Committee. The study was registered on Clinicaltrials.gov on February 26, 2014, registration identification number: NCT02075333 (available at https://www.clinicaltrials.gov/ct2/show/NCT02075333) Written informed consent was obtained from all participants. An honorarium of £140 was paid upon completion of the study.

Participants

Forty (16 males; 24 females), non-smoking, non-obese ($\bar{x} = 25.20$, SD = 2.53 kg/m^2; BMI < 30 kg/m^2; WHO, 2013), older adults ($\bar{x} = 57.75$, SD = 5.79 years) were recruited from the University campus and local community. Participants self-reported to be free from symptoms of dementia, depression, Type II diabetes, phenylketonuria or other conditions that precluded the ingestion of sucralose, and were not taking medication likely to influence glucose metabolism or cognitive function. Volunteers with impaired glucose tolerance (2 hr post-prandial capillary blood glucose $\geq$ 7.8 mmol/L) were excluded at screening. Fifteen female participants reported themselves as post-menopausal. After eligibility screening, participants were randomly assigned to a counterbalanced experimental condition order.

Glucose Measures

Capillary blood glucose was obtained via finger prick measures at – 40, - 24, - 2, + 5, + 19, + 33, + 37, and + 44 minutes relative to solution intake across study visits. Blood glucose was analysed using a YSI 2700 Glucose/Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH). Interstitial glucose was also measured in a subgroup of the total sample (5 male; 5 female) using a subcutaneous continuous glucose monitoring system (CGMS iPRO, Medtronic MiniMed, CA, USA). The CGMS was fitted the day prior to each study visit and continuously measured interstitial glucose every 5 minutes until the end of the test day. The time of solution ingestion/rinse was recorded and used to centre the response profile (0 minutes). Consequently, measures taken - 50 minutes pre- and + 40 minutes post-solution intake are reported. A finger prick measure collected upon waking on the study visit morning and measures collected by the experimenter at – 40, + 5, and + 33 minutes at each visit were used to calibrate the CGMS. Capillary blood and interstitial glucose levels are reported in millimols per litre (mmol/L).

Self-Control Tasks

All cognitive tests were presented using E prime software (Psychology Software Tools, Inc, PA, USA) on a Dell Optiplex 760 desktop computer with a 17" monitor (screen resolution 1280 x 800 pixels). Responses for both tasks were made on a keyboard spacebar.

Self-control depletor task. The Bakan task [39] was employed to deplete self-control. The Bakan is a rapid visual information processing task that requires respondents to attend to and monitor the rapid continuous presentation of single digits whilst maintaining sufficient self-control to be able to detect and respond to infrequent target stimuli (the presentation of three consecutive odd or even digits). The BAKAN can be classified within Baumeister et al.s self-control spheres of attentional and impulse control [11]. Attentional control was required to focus attention (monitoring stimuli for targets) and disregard distractions (not responding to the more frequent non-target stimuli). Impulse control was required to override the prepotent non-response to the more frequently presented non-target stimuli when infrequent target stimuli appeared. Stimuli were presented at a rate of 500 milliseconds per item, with a 100 ms inter-stimulus delay. One hundred stimuli were presented per one minute block. Participants were required to identify ten randomly presented targets (three consecutive digits) in each one minute block. Nine, one minute blocks were presented (900

hundred total trials). Stimuli were presented in the centre of a light grey display in black (bold, Courier New, 18 point) font. Target accuracy and target reaction time (RT) were recorded to monitor compliance with the task to ensure comparable engagement with the depletor task across each experimental condition.

Attention switching task. An attention switch task, originally devised by Wylie et al. [40] that combines a task-switch paradigm with a Go/noGo task was employed as a measure of self-control performance. Attention switch tasks typically require respondents to repeatedly perform a task on some trials then switch to another task when cued to do so, thus requiring the effortful suppression of a dominant response (the repeated trials). Performance on repeated trials is typically superior to performance on "switch" trial due to the time and effort needed to switch between the two tasks – the switch cost [40]. Letter-number pairs were presented on a horizontal plane in the centre of the screen for 1800 ms (120 ms inter-stimulus delay). Each character was positioned 1° to the left or right of the central fixation point (randomly determined). Letters were taken from a set containing 4 vowels (A, E, I, and U) and four consonants (G, K, M, and R). The numbers were taken from a set containing 4 even (2, 4, 6, and 8) and 4 odd numbers (3, 5, 7, and 9). The letter-number pairs were presented in two alternating colours every three trials. Respondents were required to make a Go/noGo choice based upon the colour of the letter-number pairs. For example, when letter-number pairs were red, respondents were required to respond when the letter was a vowel (Go), but not when the letter was a consonant (noGo). Alternatively, when the letter-number pairs switched to blue, respondents were required to respond when the number was even (Go), but not when the number was odd (noGo). The three trials in each task-run are split into switch, nested, and pre-switch trials. Switch trials are the first letter-number pairs presented after the task-switch (i.e., the Go/noGo colour switch). Nested and pre-switch are the subsequent repeat trials within the same task-run (see Figure 1 for stimulus configuration).

<FIGURE 1>

In total 144 trials were presented with target trials randomly presented with a probability of 50%. Eight parallel versions of the task, differing only with respect to colours used to cue the task-switch, were employed, and administered in a counterbalanced manner. Accuracy (number of correctly identified targets) and RT (target response latency) across each trial type were assessed.

206

207 **Subjective Measures**

208 The Profile of Mood States (POMS; [41]) was administered to measure transient
209 subjective mood (tension-anxiety, depression-dejection, anger-hostility, vigour-activity,
210 fatigue-inertia, and confusion-bewilderment) across each study visit.

211

212 Visual analogue scales (VAS) assessing the sensory properties of the experimental
213 solutions were employed. How "sweet", "pleasant", and "satisfying" participants found the
214 solutions were rated using 100 mm scales anchored by "*Not at all"* and *"Very".*

215

216 **Experimental Conditions**

217 All study solutions were isoweight (381.4 g) water diluted, commercially available
218 blackcurrant cordial based solutions. (Sainsbury's® High Juice Blackcurrant Squash (sucrose
219 solution) and No Added Sugar Double Strength Blackcurrant Squash (artificially sweetened
220 equivalent control solution). The solution compositions and nutritional values are shown in
221 Table 1. The sucrose solution contained 50 g of sugars, providing 25 g of glucose. The
222 placebo solution was artificially sweetened with sucralose (0.92 g of sugars).

223

224 <TABLE 1>

225

226 **Procedure**

227 All study visits were undertaken between 0700 – 1030 hr after an overnight fast
228 (approximately 10–12 hr fasted state). The timing of all procedures is shown in Figure 2.
229 Eight capillary blood samples were taken on each test visit. To control for baseline
230 differences in self-control resources, participants completed a parallel version of the attention
231 switch task upon arrival at the laboratory. Baseline POMS and the initial self-control
232 depletory task (BAKAN) were completed before rinsing or ingesting the solutions.
233 Participants were then required to ingest or rinse a sucrose or sucralose blackcurrant cordial
234 solution. In the ingest condition, participants drank the entire volume of the solution. In the
235 rinse condition, participants were instructed to take a mouthful of the solution, rinse it around
236 the mouth for 5 seconds, then spit it into an empty cup, repeating these steps until they had
237 rinsed with the entire volume of the solution. In both conditions participants were given 5
238 minutes to ingest or rinse the solutions. A palatability VAS was completed immediately post-
239 solution intake. The self-control attention switch task was administered +21 minutes post-

solution intake to allow sufficient time for glucose metabolism. Post-solution POMS ratings were collected after solution intake (+ 7 minutes and + 39 minutes).

<FIGURE 2>

Statistical Analyses

Statistical analyses were performed using SAS (Statistical Analysis System, Version 9.2; SAS Institute, Inc., Cary, NC). The SAS PROC PLAN procedure was employed to randomly generate the William Latin Square counterbalancing schedule. All data were screened and residual outliers were removed (> 2.58 SD) and residual plots inspected for deviations from normality.

A repeated measures analysis (using PROC MIXED) was employed using a mixed model with subjects as the random factor and a compound symmetry covariance structure of the repeated measures. For all glucose measurements, method (ingest and rinse), source (sucrose and sucralose), and time (glucose measurement time points) were the fixed effects in the model. For the BAKAN (depletor task), method (ingest and rinse), source (sucrose and sucralose) and trial block (1-9 mins trial blocks) were the fixed effects in the model. For the attention switch task, method (ingest and rinse), source (sucrose and sucralose) and trial (switch, nested, preswitch) were the fixed effects in the model. The potential effect of self-control depletion on peripheral glucose levels was explored by examining interstitial and capillary blood glucose over the period that participants completed the initial self-control tasks (i.e. the ego depletion period prior to solution intake). For capillary blood glucose, 3 samples at – 40, – 24, and – 2 minutes (relative to solution intake), corresponding with 10 minutes before the first attention switch task, and 2 minutes prior to, and 2 minutes immediately after, the BAKAN task, were analysed. Continuous interstitial glucose levels were analysed between – 40 and – 5 minutes (relative to solution intake) corresponding to approximately – 10 minutes before the first attention switch task and subsequently at 5 minute intervals until 5 minutes post BAKAN task. Time (blood glucose: - 40, - 24, - 2; interstitial glucose: - 40, - 35, - 30, - 25, - 20, - 15, - 10, - 5 minutes relative to solution intake) was the fixed effect in the model.

Age, sex, and BMI were entered as covariates in all models. Baseline blood glucose and subjective solution sweetness, pleasantness and satisfaction ratings were entered as

covariates in models for the attention switch task. Visit order was entered into all models as a fixed effect to rule out order effects. All models included the first and second order interactions of these stated fixed effects. Non-significant covariates and interactions were removed if they did not contribute to the model and are not reported.

Participants completed the attention switch task upon arrival at the laboratory to standardise self-control capacity prior to ego-depletion. It was considered that performance on this initial task would be too variable, compared to the standardised self-control capacity post ego-depletion, to serve as a reliable baseline comparison measure for post-depletion attention switch performance. Moreover, analyses controlling for baseline attention switch task outcomes revealed inclusion of baseline performance did not significantly alter the observed effects and were removed from statistical models.

Blood glucose area under the curve with respect to increase (AUCi) was calculated using the trapezoid method [42]. For all analyses, the significance level was set at $\alpha = 5\%$. The nominal α level was adjusted for multiple post-hoc least squares mean comparisons using the Tukey-Kramer correction [43]. All results (including figures and tables) are presented as mean and standard error of the mean (SEM).

Results

Participant Characteristics

The continuous interstitial glucose monitor subsample (IPRO) did not significantly differ from the remaining sample for age, $t(38) = -0.40$, $p = .69$, BMI, $t(38) = 0.42$, $p = .68$, or baseline fasted blood glucose, $t(38) = -1.25$, $p = .22$.

Capillary Blood Glucose

A significant source*method*time interaction was revealed for capillary blood glucose response, $F(7, 240) = 42.02$, $p < .001$. This interaction reflects a significant increase in capillary blood glucose level in the sucrose/ingest condition. Following intake of the sucrose solution, blood glucose was significantly higher at + 19, + 33, + 37, and + 44 minutes compared to – 40, - 24, – 2, and + 5 minutes relative to solution intake (all significant at $p < .001$; Figure 3). Capillary blood glucose was significantly higher in the sucrose/ingest condition at + 19, + 33, + 37, and + 44 minutes compared to the corresponding time points in all other experimental conditions ($p < .001$).

<FIGURE 3>

Capillary blood glucose AUCi further corroborates the glucose response profile data. The blood glucose AUCi response was significantly higher in the sucrose/ingest condition ($\bar{x} = 102.39 \pm 7.14$ mmol/L), $F(3,87) = 30.36$, $p < .001$, compared to all other experimental conditions (sucrose/rinse: $\bar{x} = 5.85 \pm 9.33$ mmol/L; sucralose/ingest: $\bar{x} = -9.12 \pm 8.90$ mmol/L; sucralose/rinse: $\bar{x} = -8.41 \pm 8.29$ mmol/L; $p < .001$). No significant differences were demonstrated between the remaining experimental conditions.

Interstitial Blood Glucose

Consistent with the capillary blood glucose response, an interstitial glucose response was evident in the sucrose/ingest condition only (significant source*method*time interaction, $F(18, 160) = 2.62$, $p < .001$; Figure 4). Interstitial glucose was significantly elevated from + 10 minutes onwards after sucrose solution ingestion (compared to prior measurements between - 50 to 0 minutes ($p < .001$). Interstitial glucose was significantly higher in the sucrose/ingest condition from + 10 to + 40 minutes compared to the corresponding time points in all other experimental conditions ($p < .001$).

<FIGURE 4>

Effect of Ego Depletion on Peripheral Glucose

Capillary blood glucose. A significant main effect of time $F(2, 78) = 3.75$, $p = .03$, was revealed for capillary blood glucose levels over the self-control depletion period (corresponding to – 40, –24, – 2 minutes relative to solution intake shown in Figure 3). Post hoc comparisons revealed a marginal increase in blood glucose between – 40 ($\bar{x} = 4.64 \pm 0.06$ mmol/L) and – 24 ($\bar{x} = 4.77 \pm 0.06$ mmol/L; $p = .06$) minutes, indicating an increase in blood glucose during completion of the first attention switch task. Conversely, a significant decrease was revealed between – 24 and – 2 ($\bar{x} = 4.62 \pm 0.05$ mmol/L ; $p = .04$) minutes, indicating a decrease in blood glucose during completion of the BAKAN.

Interstitial glucose. A non-significant effect of time $F(6, 54) = 0.40$, $p = .10$, was revealed for interstitial glucose levels over the self-control depletion period (corresponding to

measures between – 40 and – 5 minutes relative to solution intake shown in Figure 4) indicating no significant effect of self-control depletion on peripheral glucose levels.

Self-Control Tasks

Depletor task. A significant main effect of trial block was revealed for BAKAN target accuracy, $F(8, 312) = 20.95$, $p = .001$, and RT, $F(8, 312) = 4.25$, $p = .001$. Accuracy was significantly higher during the first two trial blocks ($p < .03$), and RT faster during the first trial block ($p < .05$), of the task compared to performance across the remaining trial blocks. This effect was independent of experimental condition and reflects a comparable temporal decline in self-control performance over task exposure at each study visit. Mean target accuracy and RT across the trial blocks are shown in Figure 5.

<FIGURE 5>

Attention Switch Performance

Reaction time. A significant main effect of method, $F(1, 39) = 4.11$, $p < .05$, trial, $F(2, 78) = 294.77$, $p < .001$, and visit, $F(3, 108) = 21.45$, $p < .001$, were revealed for attention switch RT. The method of solution intake (rinse or ingest) irrespective of source (sucrose or sucralose) significantly affected overall RT performance (i.e., independent of trial type). Post-hoc tests revealed that RT collapsed across all trials was marginally faster during rinse compared to ingest conditions ($p = .05$; Table 2).

Closer inspection of the RTs across trial suggest enhanced performance on switch trials in the sucrose rinse condition, whilst the enhancing effects of sucralose rinse are only evident in the repeat nested and preswitch trials. An additional analysis examining the differences between conditions for each specific trial type (switch, nested, preswitch), revealed a significant source*method interaction on switch trials, $F(1,37) = 4.56$, $p = .04$. However, post hoc comparisons revealed no significant RT performance difference on switch trials between conditions (faster RT after rinsing with sucrose vs. ingesting sucrose and rinsing with sucralose $p = .10$).

<TABLE 2>

Participants overall RT decreased over the study visits indicating a practice effect. However, no interaction with source or method suggests counterbalancing ensured this effect was equally balanced across the experimental conditions

Accuracy. A significant trial*visit interaction $F(6, 195) = 2.71$, $p = .02$, main effects of trial, $F(2, 78) = 23.72$, $p < .001$, visit, $F(3, 104) = 21.65$, $p < .001$, and a marginal main effect of method, $F(1, 39) = 3.85$, $p = .06$, were revealed for attention switch accuracy (Table 2).

The trial*visit interaction reflects significantly lower accuracy on switch trials at visit 1 compared to visits 2 and 3, and on preswitch trials at visit 1 compared to visits 2, 3 , and 4; this is consistent with a practice effect. However, no interaction with source or method suggests counterbalancing ensured this effect was equally balanced across the experimental conditions.

Post hoc tests revealed the marginal main effect of method to be reflective of non-significantly higher accuracy during rinse compared to ingest conditions ($p = .09$). Additional analyses revealed no significant differences between solution conditions for each specific trial type. It should be noted that many participants' accuracy was close to ceiling.

The main effect of trial for both attention switch RT and accuracy reflects significantly lower performance on switch vs nested and preswitch trials ($p < .001$) and preswitch vs nested trials (RT: $p < .05$; accuracy: $p = .01$), indicating the cognitive cost of switch between task contingencies. However, this was independent of experimental conditions so does not reflect an effect of the intervention.

To permit a more direct comparison with previous studies reporting the specific facilitative effect of ingesting carbohydrates vs artificially sweetened drinks (e.g., [18]), and rinsing carbohydrates vs artificially sweetened drinks (e.g., [15]), two separate analyses comparing the ingestion of sucrose vs. sucralose and comparing the rinsing of sucrose vs. sucralose solutions were conducted.

Ingest. No significant effects of ingesting sucrose or sucralose were revealed for switch task accuracy or RT. Main effects of trial (accuracy: $F(2,78) = 11.72$, $p < .001$; RT: $F(2,78) = 151.45$, $p < .001$) and visit (accuracy: $F(3,34) = 10.75$, $p < .001$; RT: $F(3,34) =$

12.79, p < .001) reflected greater accuracy and RT on nested and preswitch vs switch trials, and improved performance over study visits (p < .05).

Rinse. No significant effects of rinsing sucrose or sucralose were revealed for switch task accuracy or RT. Main effects of trial (accuracy: F(2,77) = 14.38, p < .001; RT: F(2,76) = 145.63, p < .001) and visit (accuracy: F(3,34) = 12.82, p < .001; RT: F(3,34) = 5.72, p = .003) reflected greater accuracy and RT on nested and preswitch vs switch trials, and improved performance over study visits (p < .05). A non-significant source (sucrose vs sucralose)*trial interaction was revealed for RT, F(2,79) = 2.45, p = .09. Post hoc comparison revealed no significant differences in RT performance between the rinse conditions.

Subjective Response

Subjective mood (POMS). Significant baseline*source*method, F(1,221) = 11.97, p < .001, source*method, F(1,28) = 7.43, p = .01, baseline*method, F(1,217) = 5.22, p = .02, interactions and an effect of baseline, F(1,217) = 67.98, p < .001, were revealed for subjective fatigue-inertia rating. A positive relationship between baseline and post-solution overall fatigue rating was demonstrated. This positive association was strongest in the sucralose/rinse and weakest in the sucrose/ingest condition specifically at higher fatigue loads. This suggests ingestion of glucose reduced fatigue more than rinsing with sucralose in those reporting high baseline fatigue. Overall, higher subjective fatigue ratings were shown in rinse ($\bar{x} = 4.22 \pm 0.35$) compared to ingest conditions ($\bar{x} = 3.39 \pm 0.29$; p = .01). Specifically, significantly higher fatigue was reported following rinsing of sucralose ($\bar{x} = 4.65 \pm 0.5$) compared to ingesting sucralose ($\bar{x} = 3.28 \pm 0.43$; p = .03). Marginally higher fatigue ratings were also reported after rinsing with sucrose ($\bar{x} = 3.78 \pm 0.47$) compared to ingesting sucralose (p = .06).

Examination of the remaining POM dimensions revealed no further significant effects of exposure to the experimental conditions on subjective mood.

Solution Palatability

Participants rated the sucrose solutions ($\bar{x} = 72.55 \pm 2.05$) to be significantly sweeter than the sucralose ($\bar{x} = 66.75 \pm 2.27$) solutions (p = .01; main effect of source, F(1,39) = 7.44, p = .001). However, solution rinsing ($\bar{x} = 71.77 \pm 1.94$) was rated to be significantly

sweeter than ingesting ($\bar{x}$ = 67.53 ± 2.38) the solutions (p = .05; main effect of method, F(1,39) = 3.95, p = .05). This likely reflects the longer retention of solutions in the oral cavity in the rinse conditions. The sucrose solutions ($\bar{x} = 59.66 \pm 2.91$) were also perceived to be more pleasant than the sucralose solutions ($\bar{x} = 51.53 \pm 3.06$; p = .01; main effect of source, F(1,39) = 9.60, p = .001). Specifically, ingesting the sucrose solution ($\bar{x} = 64.95 \pm 3.67$) was rated as significantly more pleasant than all other conditions (p < .02; source*method interaction, F(1,39) = 7.73, p = .01). Participants also rated the ingestion ($\bar{x} = 57.12 \pm 2.68$) of solutions to be significantly more satisfying than rinsing ($\bar{x} = 44.99 \pm 2.91$; p = .001; main effect of method, F(1,39) = 17.03, p = .01).

Discussion

Carbohydrates have been associated with a positive effect on depleted self-control task performance. This effect has been the subject of both metabolic and motivational explanations. The findings from the present study contribute to the current understanding of the relationship between carbohydrates and self-control in a number of ways. Firstly, the findings contradict metabolic accounts of the relationship between self-control and carbohydrate metabolism. Despite the use of high precision laboratory standard measurement of capillary blood and interstitial glucose, no consistent effects of self-control exertion on glucose metabolism were observed. A small, but significant drop in capillary blood glucose was demonstrated over the period participants completed the BAKAN depletion task. However, this constituted an average decrease of 0.15 mmol/L. This is lower than the peripheral blood glucose decrease under depletion conditions previously reported (0.33 mmol/L [14]). A comparable increase (0.13 mmol/L) was also demonstrated during exposure to the initial attention switch task; therefore, this finding likely reflects variation in endogenous blood glucose levels and/or precision variability of the glucose analyser. Furthermore, self-control exertion had no effect on interstitial glucose levels which were continuously measured throughout the ego-depletion period, and can thus be considered a more robust measure of this effect. This supports previous evidence that the moderation of peripheral glucose by self-control exertion is unlikely (16, 30, 15) and contradicts evidence directly linking glucose metabolism to self-control (3, 14). Inconsistency in the literature may stem from the use of less reliable and precise commercially available capillary blood glucose monitors which are not sufficiently sensitive to measure fluctuations in the euglycaemic

range [44, 45]. The use of a subcutaneous continuous glucose monitor also confirmed, for the first time, the lack of this effect in interstitial fluid.

The contention that glucose administration has "a large homogenous effect" on ego depletion (p. 514; [11]) was not supported. No discernible difference in self-control performance under conditions of ego depletion was found despite large concomitant increases in both blood and interstitial glucose levels. This lack of effect in older adults replicates findings demonstrated in a young adult sample [31] and contributes to growing evidence that the role of glucose as the physical mediator of self-control has been overstated [16]. The non-energetic capacity of carbohydrate sensing in the mouth to moderate self-control performance has been at the forefront of criticism of the metabolic-based resource strength model. The present study also failed to demonstrate any specific, significant effect of sensing carbohydrate in the mouth on depleted self-control performance. This contradicts previous evidence of the capacity of carbohydrate rinsing to protect performance [21 ,15, 22]. However, the positive effect of carbohydrate rinsing has not been consistently reported [30].

The act of rinsing both a caloric and an artificially sweetened solution was associated with superior performance on an attention switch task compared to ingestion of the same solutions. It is important to note that improved attention switch performance after rinsing the solutions was marginal ($p = .05$) and very small (RT saving 17 ms; Cohen's $d = .1$). This effect is certainly not as robust as previous demonstrations of the facilitative effects of rinsing (e.g., $d = .63, .73$ [15]). The effect of rinsing on accuracy was marginal and likely influenced by ceiling effects. However, a positive effect of rinsing in general on cognitive performance is difficult to assimilate with existing evidence of the effect of rinsing carbohydrate and artificially sweetened solutions. The potential effect of ingesting the solutions having a greater fatiguing effect than rinsing, due to the digestive processes required, is contradicted by higher subjective levels of fatigue in rinse conditions, and evidence of a specific restorative effect of sucrose in those reporting higher fatigue at baseline. Previous evidence of the positive effects of rinsing has been attributed to the specific sensing of energy in the oral cavity. Oral energy sensing of carbohydrate may stimulate activity in neural regions associated with exertion of self-control (namely the anterior cingulate cortex [ACC]) thus countering reduced activity when depleted. Oral sensing may also activate neural reward pathways shifting the motivational state towards persistence [24, 15]. This proposed mechanism cannot easily explain the observation of general beneficial effects of rinsing with both

sucrose and sucralose that were observed in the current study. fMRI studies have located divergent neural activation for caloric and artificially sweetened oral solutions. For example, stronger activation of the primary taste areas (anterior insula and frontal operculum), prefrontal cortex, and reward circuit regions (striatum) is evident after tasting sucrose compared to an artificially sweetened solution [24, 47]. Divergent activation by caloric and artificially sweetened oral solutions has also been reported in the amygdala, median cingulate, thalamus and pre-central gyrus [48, 49].

However, the proposed mechanisms of oral sensing remain speculative and unverified, and neural areas activated by oral carbohydrate sensing are rather heterogeneous. Furthermore, a divergent response across energy content has not been consistently shown. van Rijn et al. [50] reported no overall difference in neural activation for caloric (maltodextrin and maltodextrin + sucralose) and sucralose solutions. Activation of reward circuit areas (striatum) after tasting caloric and non/low-caloric solutions (including water) were also indistinguishable. Divergent neural activation was only demonstrated when hunger state was taken into account. Greater activation of the median cingulate, thalamus, anterior insula and inferior frontal gyrus, was revealed after tasting a caloric solution in a satiated compared to hungry state. Thus energy sensing may be a hunger state dependent process. This emphasises that the mechanisms assumed to underpin the effects of oral energy sensing on self-control are yet to be fully elucidated.

Lange and Eggert [30] attempted to further clarify how the proposed rewarding effect of oral sensing acts to moderate self-control by manipulating the temporal relationship between ingestion and rinsing of carbohydrate and self-control tasks. Oral sensing of carbohydrate may operate via (i) retrospectively rewarding initial self-control exertion if administered after the initial depletory task, or (ii) prospectively indicating the availability of future resources signalling 'affordable' continued exertion of self-control if administered prior to the secondary ego depleted task [30]. No effect of rinsing, or ingesting, carbohydrates on self-control were observed. Such findings are incompatible with the assumed rewarding effect of oral sensing. Psychological manipulations (e.g., thinking about a cherished value [29]) have also been shown to attenuate depleted self-control performance. Mere perception of feeling less (versus more) depleted, irrespective of actual level of depletion, also results in better self-control performance [51]. Therefore, self-control capacity appears sensitive to multiple factors independent of metabolism or the rewarding properties of energy sensing.

539

540 Findings demonstrate that RT in general, i.e., independent of trial type, was faster
541 after rinsing, independent of carbohydrate content. The exertion of self-control on this task
542 specifically relates to the effortful suppression of the dominant response to repeated trials
543 when responding to switch trials. It is therefore debatable if a facilitation of RT, independent
544 of trial, is indicative of a clear effect on self-control performance. A facilitative effect on self-
545 control performance would be more clearly indexed by faster RT or greater accuracy on
546 switch trials compared to repeat trials. However, across all conditions, performance on
547 preswitch trial was lower than nested trials. This performance deficit on preswitch trials is
548 likely reflective of a preparatory response or inhibition of a premature response to the
549 impending task switch. Therefore, whilst performance on the switch trials relative to repeated
550 trials is the primary indicator of self-control performance, performance across the task in
551 general can still be considered a measure of self-control. Comparisons of performance on
552 each trial type between conditions did reveal a trend for faster RT on switch trials after
553 rinsing sucrose ($p = .10$); enhancement after sucralose rinsing was confined to repeat trials.
554 This provides only very limited support for the non-metabolic enhancing effect of oral sensing
555 carbohydrates on depleted self-control performance.
556

557 The strengths of the reported study lie in the robust methodology adopted. Highly
558 precise methods of assessing the metabolic effects of ingesting and rinsing carbohydrates and
559 a rigorous standardised, repeated measures, counterbalanced crossover design were applied.
560 The cognitive tasks employed to deplete and measure self-control performance were also
561 well-established and validated measures of performance. This contrasts with previous studies
562 that have adopted less standardised methods of depleting self-control (e.g., writing about
563 one's death [3]; a high score on a questionnaire assessing attitudes towards homosexuality
564 [18]). To detect an effect of carbohydrate ingestion as large as that reported by Hagger et al.
565 [11] ($d = .75$) or Gailliot et al. [11] ($d = .55$), sample sizes of $n = 16$ and $n = 28$ would be
566 required respectively using the employed design. Similarly, a sample size of $n = 22$ would be
567 required to detect an effect of rinsing carbohydrate of the magnitude reported by Molden et
568 al. [15] ($d = .63$; all $\alpha = .05$, $1 - \beta = .8$). Therefore, the lack of convincing effects in this sample
569 of 40 older adults is unlikely to be due to an insufficient level of power. However, a number
570 of additional factors are worthy of discussion. Different self-control tasks were employed to
571 deplete and assess ego depleted performance in the present study. The use of differing tasks
572 should not be expected to unduly influence the findings considering the assumption that self-

control capacity is mediated by a common, modality independent, resource [11]. Furthermore, the positive effects of carbohydrates on self-control performance, and failed attempts to replicate the effects, have been demonstrated using the same [20, 31] and dissimilar [21, 30] tasks.

In this study, the placebo solutions were sweetened with sucralose which, whilst sufficiently low in energy to be considered non-caloric (< 4 kcal in study solutions), contains a small amount of maltodextrin filler (< 1 g in study solutions). The majority of studies examining the effects of rinsing carbohydrates have employed artificial sweeteners completely free from carbohydrates (e.g., aspartame [15, 21]). Therefore, it could be argued that the facilitative effects of rinsing with both sucrose and sucralose may be indicative of an enhancing effect of carbohydrate even at very low levels. However, specific enhancing effects of rinsing glucose but not sucralose have been reported [22 46] which contradicts this proposition.

Evidence that greater initial exertion on multiple tasks of self-control does not inevitably result in more severe subsequent performance decrement – as may be assumed by the self-control resource model – has been reported [46]. Indeed, the inclusion of multiple initial depletory self-control tasks has been shown to increase performance [52]. Therefore, the initial pre-solution intake exposure to the attention switch task to standardise baseline self-control resources may have influenced subsequent self-control outcomes. However, this would not explain why improved performance was only demonstrated in the rinse conditions since all visits were strictly standardised and counterbalanced.

The recruitment of an older adult sample was informed by evidence of greater potential efficacy of glucose administration in populations with increased likelihood of disrupted metabolic or cognitive activity (e.g., [52, 33, 35]. It is however acknowledged that ego depletion deficits may not be as potent in older versus younger samples (more evident in < 25 vs 40 – 65 year olds [53]).

Finally, participants reported a discernible taste perception difference between the experimental solutions which may be argued to have unduly influenced the results. However, the inclusion of perceived sweetness, satisfaction and pleasantness rating in statistical models did not significantly affect the outcome variables and modulation of performance was observed independently of source.

Conclusions

Findings contribute to recent evidence casting doubts upon a specific role of carbohydrate in self-control performance. Exertion of self-control did not moderate blood or interstitial glucose, nor did metabolism or oral sensing of sucrose significantly affect self-control performance in the ego depleted state. In sum, findings do not support the proposition that carbohydrate is vital for self-control in older adults and suggests that the role of glucose as the physical mediator of self-control has been overstated.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors have full control of all primary data and will permit access to review if requested. The funding agent provided editorial assistance in the completion of the draft for publication (KN). The original concept, review of literature, and study design was conceived by LD and CL. The collection (with assistance of FC and KS), analysis and interpretation of the data were completed by the corresponding author (NB). The corresponding author completed the draft for publication with editorial assistance from LD, CL, and RA.

631 **TABLES**

632

633 Table 1 Solution compositions and nutritional content

Solution	Serving	Solution Composition	Sugar Content	Kcal
Sucrose	381.4g	125.9g cordial + 255.5g water	50g	200
Sucralose	381.4g	63.5g cordial + 317.5g water	0.92g	3.7

Table 2 Descriptive statistics of attention switch task performance outcomes according to experimental condition*trial and total performance*method of solution intake (ingest vs. rinse). Mean ± SEM are shown

Experimental Condition	**Reaction Time (ms)**								**Accuracy**							
	Trial								Trial							
	Switch		Nested		Preswitch				Switch		Nested		Preswitch			
	X	*SEM*	*X*	*SEM*	*X*	SEM			*X*	*SEM*	*X*	*SEM*	*X*	*SEM*		
Sucrose/ingest	1154.45	19.49	931.30	20.90	950.71	20.81			21.33	0.37	22.56	0.26	22.21	0.33		
Sucrose/rinse	1110.18	18.72	910.97	21.78	947.27	24.34			21.67	0.37	23.05	0.18	22.42	0.29		
Sucralose/ingest	1148.35	25.34	931.16	23.09	944.94	22.55			21.50	0.47	22.15	0.43	21.49	0.50		
Sucralose/rinse	1157.16	20.93	915.80	22.87	933.54	20.09	**Total**		21.43	0.41	22.41	0.38	21.74	0.49	**Total**	
							X	*SEM*							*X*	*SEM*
Ingest							1010.49	10.91							21.87	0.16
Rinse							993.49	10.83**							22.12	0.15*

** p = .05 * p = .09

Figure 1 Attention switch task stimulus configuration showing seven consecutive trials. Participants were required to make a Go/noGo response if the letter shown was a vowel or consonant (red coloured stimuli), and if the number shown was odd or even (green coloured stimuli). The task run switched between the two categorisation Go/noGo tasks every third trial. Figure adapted with permission from Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003). Task switching: a high-density electrical mapping study. Neuroimage, 20(4), 2322-2342

Figure 2 Procedural timeline

Figure 3 Mean capillary blood glucose response (mmol/L) according to experimental condition

Figure 4 Mean interstitial glucose response (mmol/L) according to experimental condition. Exposure to the experimental solutions is centred at 0 minutes which represents time of solution intake

Figure 5 Mean Bakan target accuracy (A) and RT (B) across each one minute trial block according to experimental condition

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