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

2
3 Boyle, N. B. ^{1*}, Lawton, C.L. ¹, Allen R. ¹, Croden, F.¹, Smith K. ², Dye, L. ¹

4
5 ¹ School of Psychology, University of Leeds, Woodhouse Ln., Leeds, UK

6 ²Leeds Beckett University, Woodhouse Ln., Leeds, UK

7 * Corresponding Author: Address: School of Psychology, University of Leeds, LS2 9JT;

8 Email: n.b.boyle@leeds.ac.uk; Phone: +44 (0)113 3430540; Fax: +44 (0)113 3435749

9
10
11 **Keywords:** Self-control; Glucose; Ego-depletion; Oral rinsing; Capillary blood glucose

12 **Short title:** Self-control, Ego-depletion, & Carbohydrates

Abstract

15
16 Self-control tasks appear to deplete a limited resource resulting in reduced subsequent self-
17 control performance; a state of *ego depletion*. Evidence of reduced peripheral glucose by
18 exertion of self-control, and attenuation of ego depletion by carbohydrate metabolism
19 underpins the proposition that this macronutrient provides the energetic source of self-
20 control. However, the demonstration of positive, non-metabolic effects on ego depletion
21 when merely sensing carbohydrates orally contradicts this hypothesis. Recent studies have
22 also failed to support both metabolic and non-metabolic accounts. The effects of ingesting or
23 rinsing a carbohydrate (sucrose) and an artificially sweetened (sucralose) solution on
24 capillary blood and interstitial glucose, and depleted self-control performance were examined
25 in older adults. Forty, healthy, adults (50–65 years) ingested and rinsed sucrose and sucralose
26 solutions in a 2(method) x 2(source), fully counterbalanced, repeated measures, crossover
27 design. Capillary blood and interstitial glucose responses were assayed. Depleted self-control
28 performance (induced by the Bakan visual processing task) on an attention switch task was
29 assessed under each study condition. Ego depletion had no consistent effects on peripheral
30 glucose levels and no significant effects of ingesting or rinsing sucrose on self-control were
31 observed. The act of rinsing the solutions, independent of energetic content, resulted in a
32 small, **non-significant** enhancement of performance on the attention switch task relative to
33 ingesting the same solutions (RT: $p = .05$; accuracy: $p = .09$). In conclusion, a metabolic
34 account of self-control was not supported. Whilst a positive effect of rinsing on depleted self-
35 control performance was demonstrated, this was independent of energetic content. Findings
36 suggest glucose is an unlikely physiological analogue for self-control resources.

37

38

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

86

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

96

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

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

114 **Methods**

115 **Design**

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

130 **Participants**

131 Forty (16 males; 24 females), non-smoking, non-obese ($\bar{x} = 25.20$, $SD = 2.53$ kg/m²;
132 BMI < 30 kg/m²; WHO, 2013), older adults ($\bar{x} = 57.75$, $SD = 5.79$ years) were recruited from
133 the University campus and local community. Participants self-reported to be free from
134 symptoms of dementia, depression, Type II diabetes, phenylketonuria or other conditions that
135 precluded the ingestion of sucralose, and were not taking medication likely to influence
136 glucose metabolism or cognitive function. Volunteers with impaired glucose tolerance (2 hr
137 post-prandial capillary blood glucose ≥ 7.8 mmol/L) were excluded at screening. Fifteen
138 female participants reported themselves as post-menopausal. After eligibility screening,
139 participants were randomly assigned to a counterbalanced experimental condition order.

140

141 **Glucose Measures**

142 Capillary blood glucose was obtained via finger prick measures at – 40, - 24, - 2, + 5,
143 + 19, + 33, + 37, and + 44 minutes relative to solution intake across study visits. Blood
144 glucose was analysed using a YSI 2700 Glucose/Lactate Analyzer (Yellow Springs
145 Instruments, Yellow Springs, OH). Interstitial glucose was also measured in a subgroup of
146 the total sample (5 male; 5 female) using a subcutaneous continuous glucose monitoring
147 system (CGMS iPRO, Medtronic MiniMed, CA, USA). The CGMS was fitted the day prior
148 to each study visit and continuously measured interstitial glucose every 5 minutes until the
149 end of the test day. The time of solution ingestion/rinse was recorded and used to centre the
150 response profile (0 minutes). Consequently, measures taken - 50 minutes pre- and + 40
151 minutes post-solution intake are reported. A finger prick measure collected upon waking on
152 the study visit morning and measures collected by the experimenter at – 40, + 5, and + 33
153 minutes at each visit were used to calibrate the CGMS. Capillary blood and interstitial
154 glucose levels are reported in millimols per litre (mmol/L).

155

156 **Self-Control Tasks**

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

160

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

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

178

179 **Attention switching task.** An attention switch task, originally devised by Wylie et al.
180 ⁽⁴⁰⁾ that combines a task-switch paradigm with a Go/noGo task was employed as a measure of
181 self-control performance. Attention switch tasks typically require respondents to repeatedly
182 perform a task on some trials then switch to another task when cued to do so, thus requiring
183 the effortful suppression of a dominant response (the repeated trials). Performance on
184 repeated trials is typically superior to performance on “switch” trial due to the time and effort
185 needed to switch between the two tasks – the *switch cost* ⁽⁴⁰⁾. Letter-number pairs were
186 presented on a horizontal plane in the centre of the screen for 1800 ms (120 ms inter-stimulus
187 delay). Each character was positioned 1° to the left or right of the central fixation point
188 (randomly determined). Letters were taken from a set containing 4 vowels (A, E, I, and U)
189 and four consonants (G, K, M, and R). The numbers were taken from a set containing 4 even
190 (2, 4, 6, and 8) and 4 odd numbers (3, 5, 7, and 9). The letter-number pairs were presented in
191 two alternating colours every three trials. Respondents were required to make a Go/noGo
192 choice based upon the colour of the letter-number pairs. For example, when letter-number
193 pairs were red, respondents were required to respond when the letter was a vowel (Go), but
194 not when the letter was a consonant (noGo). Alternatively, when the letter-number pairs
195 switched to blue, respondents were required to respond when the number was even (Go), but
196 not when the number was odd (noGo). The three trials in each task-run are split into switch,
197 nested, and pre-switch trials. Switch trials are the first letter-number pairs presented after the
198 task-switch (i.e., the Go/noGo colour switch). Nested and pre-switch are the subsequent
199 repeat trials within the same task-run (see Figure 1 for stimulus configuration).

200 <FIGURE 1>

201 In total 144 trials were presented with target trials randomly presented with a
202 probability of 50%. Eight parallel versions of the task, differing only with respect to colours
203 used to cue the task-switch, were employed, and administered in a counterbalanced manner.
204 Accuracy (number of correctly identified targets) and RT (target response latency) across
205 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-

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

242

243 <FIGURE 2>

244

245 **Statistical Analyses**

246 Statistical analyses were performed using SAS (Statistical Analysis System, Version
247 9.2; SAS Institute, Inc., Cary, NC). The SAS PROC PLAN procedure was employed to
248 randomly generate the William Latin Square counterbalancing schedule. All data were
249 screened and residual outliers were removed (> 2.58 SD) and residual plots inspected for
250 deviations from normality.

251

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

271

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

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

278

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

286

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

292

Results

293 Participant Characteristics

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

297

298 Capillary Blood Glucose

299 A significant source*method*time interaction was revealed for capillary blood
300 glucose response, $F(7, 240) = 42.02$, $p < .001$. This interaction reflects a significant increase
301 in capillary blood glucose level in the sucrose/ingest condition. Following intake of the
302 sucrose solution, blood glucose was significantly higher at + 19, + 33, + 37, and + 44 minutes
303 compared to - 40, - 24, - 2, and + 5 minutes relative to solution intake (all significant at $p <$
304 $.001$; Figure 3). Capillary blood glucose was significantly higher in the sucrose/ingest
305 condition at + 19, + 33, + 37, and + 44 minutes compared to the corresponding time points in
306 all other experimental conditions ($p < .001$).

307

308 <FIGURE 3>

309

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

316

317 **Interstitial Blood Glucose**

318 Consistent with the capillary blood glucose response, an interstitial glucose response
319 was evident in the sucrose/ingest condition only (significant source*method*time interaction,
320 $F(18, 160) = 2.62$, $p < .001$; Figure 4). Interstitial glucose was significantly elevated from +
321 10 minutes onwards after sucrose solution ingestion (compared to prior measurements
322 between - 50 to 0 minutes ($p < .001$). Interstitial glucose was significantly higher in the
323 sucrose/ingest condition from + 10 to + 40 minutes compared to the corresponding time
324 points in all other experimental conditions ($p < .001$).

325

326 <FIGURE 4>

327

328 **Effect of Ego Depletion on Peripheral Glucose**

329 **Capillary blood glucose.** A significant main effect of time $F(2, 78) = 3.75$, $p = .03$,
330 was revealed for capillary blood glucose levels over the self-control depletion period
331 (corresponding to - 40, -24, - 2 minutes relative to solution intake shown in Figure 3). Post
332 hoc comparisons revealed a marginal increase in blood glucose between - 40 ($\bar{x} = 4.64 \pm$
333 0.06 mmol/L) and - 24 ($\bar{x} = 4.77 \pm 0.06$ mmol/L; $p = .06$) minutes, indicating an increase in
334 blood glucose during completion of the first attention switch task. Conversely, a significant
335 decrease was revealed between - 24 and - 2 ($\bar{x} = 4.62 \pm 0.05$ mmol/L ; $p = .04$) minutes,
336 indicating a decrease in blood glucose during completion of the BAKAN.

337

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

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

342

343 **Self-Control Tasks**

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

351

352 <FIGURE 5>

353

354 **Attention Switch Performance**

355 **Reaction time.** A significant main effect of method, $F(1, 39) = 4.11, p < .05$, trial,
356 $F(2, 78) = 294.77, p < .001$, and visit, $F(3, 108) = 21.45, p < .001$, were revealed for attention
357 switch RT. The method of solution intake (rinse or ingest) irrespective of source (sucrose or
358 sucralose) significantly affected overall RT performance (i.e., independent of trial type).
359 Post-hoc tests revealed that RT collapsed across all trials was marginally faster during rinse
360 compared to ingest conditions ($p = .05$; Table 2).

361

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

370

371 <TABLE 2>

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

375

376 **Accuracy.** A significant trial*visit interaction $F(6, 195) = 2.71, p = .02$, main effects
377 of trial, $F(2, 78) = 23.72, p < .001$, visit, $F(3, 104) = 21.65, p < .001$, and a marginal main
378 effect of method, $F(1, 39) = 3.85, p = .06$, were revealed for attention switch accuracy (Table
379 2).

380

381 The trial*visit interaction reflects significantly lower accuracy on switch trials at visit
382 1 compared to visits 2 and 3, and on preswitch trials at visit 1 compared to visits 2, 3, and 4;
383 this is consistent with a practice effect. However, no interaction with source or method
384 suggests counterbalancing ensured this effect was equally balanced across the experimental
385 conditions.

386

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

391

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

397

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

403

404 **Ingest.** No significant effects of ingesting sucrose or sucralose were revealed for
405 switch task accuracy or RT. Main effects of trial (accuracy: $F(2,78) = 11.72, p < .001$; RT:
405 $F(2,78) = 151.45, p < .001$) and visit (accuracy: $F(3,34) = 10.75, p < .001$; RT: $F(3,34) =$

406 12.79, $p < .001$) reflected greater accuracy and RT on nested and preswitch vs switch trials,
407 and improved performance over study visits ($p < .05$).

408

409 **Rinse.** No significant effects of rinsing sucrose or sucralose were revealed for switch
410 task accuracy or RT. Main effects of trial (accuracy: $F(2,77) = 14.38$, $p < .001$; RT: $F(2,76) =$
411 145.63 , $p < .001$) and visit (accuracy: $F(3,34) = 12.82$, $p < .001$; RT: $F(3,34) = 5.72$, $p =$
412 $.003$) reflected greater accuracy and RT on nested and preswitch vs switch trials, and
413 improved performance over study visits ($p < .05$). A non-significant source (sucrose vs
414 sucralose)*trial interaction was revealed for RT, $F(2,79) = 2.45$, $p = .09$. Post hoc comparison
415 revealed no significant differences in RT performance between the rinse conditions.

416

417 **Subjective Response**

418 **Subjective mood (POMS).** Significant baseline*source*method, $F(1,221) = 11.97$, p
419 $< .001$, source*method, $F(1,28) = 7.43$, $p = .01$, baseline*method, $F(1,217) = 5.22$, $p = .02$,
420 interactions and an effect of baseline, $F(1,217) = 67.98$, $p < .001$, were revealed for
421 subjective fatigue-inertia rating. A positive relationship between baseline and post-solution
422 overall fatigue rating was demonstrated. This positive association was strongest in the
423 sucralose/rinse and weakest in the sucrose/ingest condition specifically at higher fatigue
424 loads. This suggests ingestion of glucose reduced fatigue more than rinsing with sucralose in
425 those reporting high baseline fatigue. Overall, higher subjective fatigue ratings were shown in
426 rinse ($\bar{x} = 4.22 \pm 0.35$) compared to ingest conditions ($\bar{x} = 3.39 \pm 0.29$; $p = .01$).
427 Specifically, significantly higher fatigue was reported following rinsing of sucralose ($\bar{x} =$
428 4.65 ± 0.5) compared to ingesting sucralose ($\bar{x} = 3.28 \pm 0.43$; $p = .03$). Marginally higher
429 fatigue ratings were also reported after rinsing with sucrose ($\bar{x} = 3.78 \pm 0.47$) compared to
430 ingesting sucralose ($p = .06$).

431

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

434

435 **Solution Palatability**

436 Participants rated the sucrose solutions ($\bar{x} = 72.55 \pm 2.05$) to be significantly sweeter
437 than the sucralose ($\bar{x} = 66.75 \pm 2.27$) solutions ($p = .01$; main effect of source, $F(1,39) =$
438 7.44 , $p = .001$). However, solution rinsing ($\bar{x} = 71.77 \pm 1.94$) was rated to be significantly

439 sweeter than ingesting ($\bar{x} = 67.53 \pm 2.38$) the solutions ($p = .05$; main effect of method,
440 $F(1,39) = 3.95, p = .05$). This likely reflects the longer retention of solutions in the oral cavity
441 in the rinse conditions. The sucrose solutions ($\bar{x} = 59.66 \pm 2.91$) were also perceived to be
442 more pleasant than the sucralose solutions ($\bar{x} = 51.53 \pm 3.06; p = .01$; main effect of source,
443 $F(1,39) = 9.60, p = .001$). Specifically, ingesting the sucrose solution ($\bar{x} = 64.95 \pm 3.67$) was
444 rated as significantly more pleasant than all other conditions ($p < .02$; source*method
445 interaction, $F(1,39) = 7.73, p = .01$). Participants also rated the ingestion ($\bar{x} = 57.12 \pm 2.68$)
446 of solutions to be significantly more satisfying than rinsing ($\bar{x} = 44.99 \pm 2.91; p = .001$; main
447 effect of method, $F(1,39) = 17.03, p = .01$).

448

449

Discussion

450

451 Carbohydrates have been associated with a positive effect on depleted self-control
452 task performance. This effect has been the subject of both metabolic and motivational
453 explanations. The findings from the present study contribute to the current understanding of
454 the relationship between carbohydrates and self-control in a number of ways. Firstly, the
455 findings contradict metabolic accounts of the relationship between self-control and
456 carbohydrate metabolism. Despite the use of high precision laboratory standard measurement
457 of capillary blood and interstitial glucose, no consistent effects of self-control exertion on
458 glucose metabolism were observed. A small, but significant drop in capillary blood glucose
459 was demonstrated over the period participants completed the BAKAN depletion task.
460 However, this constituted an average decrease of 0.15 mmol/L. This is lower than the
461 peripheral blood glucose decrease under depletion conditions previously reported (0.33
462 mmol/L^[14]). A comparable increase (0.13 mmol/L) was also demonstrated during exposure
463 to the initial attention switch task; therefore, this finding likely reflects variation in
464 endogenous blood glucose levels and/or precision variability of the glucose analyser.
465 Furthermore, self-control exertion had no effect on interstitial glucose levels which were
466 continuously measured throughout the ego-depletion period, and can thus be considered a
467 more robust measure of this effect. This supports previous evidence that the moderation of
468 peripheral glucose by self-control exertion is unlikely^(16, 30, 15) and contradicts evidence
469 directly linking glucose metabolism to self-control^(3, 14). Inconsistency in the literature may
470 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

471 range ^(44, 45). The use of a subcutaneous continuous glucose monitor also confirmed, for the
472 first time, the lack of this effect in interstitial fluid.

473

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

486

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

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

512

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

525

526 Lange and Eggert ⁽³⁰⁾ attempted to further clarify how the proposed rewarding effect
527 of oral sensing acts to moderate self-control by manipulating the temporal relationship
528 between ingestion and rinsing of carbohydrate and self-control tasks. Oral sensing of
529 carbohydrate may operate via *(i)* retrospectively rewarding initial self-control exertion if
530 administered after the initial depletory task, or *(ii)* prospectively indicating the availability of
531 future resources signalling ‘affordable’ continued exertion of self-control if administered
532 prior to the secondary ego depleted task ⁽³⁰⁾. No effect of rinsing, or ingesting, carbohydrates
533 on self-control were observed. Such findings are incompatible with the assumed rewarding
534 effect of oral sensing. Psychological manipulations (e.g., thinking about a cherished value
535 ⁽²⁹⁾) have also been shown to attenuate depleted self-control performance. Mere perception of
536 feeling less (versus more) depleted, irrespective of actual level of depletion, also results in
537 better self-control performance ⁽⁵¹⁾. Therefore, self-control capacity appears sensitive to
538 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-

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

576

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

586

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

595

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

601

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

607

608

609 **Conclusions**

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

616

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620

621 **Conflict of Interest**

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

629

630

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

634

635 Table 2 Descriptive statistics of attention switch task performance outcomes according to experimental condition*trial and total

636 performance*method of solution intake (ingest vs. rinse). Mean \pm SEM are shown

Experimental Condition	Reaction Time (ms)						Accuracy					
	Trial						Trial					
	Switch		Nested		Preswitch		Switch		Nested		Preswitch	
	<i>X</i>	<i>SEM</i>	<i>X</i>	<i>SEM</i>	<i>X</i>	<i>SEM</i>	<i>X</i>	<i>SEM</i>	<i>X</i>	<i>SEM</i>	<i>X</i>	<i>SEM</i>
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					
							<i>X</i>	<i>SEM</i>			<i>X</i>	<i>SEM</i>
Ingest							1010.49	10.91			21.87	0.16
Rinse							993.49	10.83**			22.12	0.15*

637 ** $p = .05$ * $p = .09$

638

639

640 **Figure 1** Attention switch task stimulus configuration showing seven consecutive trials.

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

646

647 **Figure 2** Procedural timeline

648

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

651

652 **Figure 4** Mean interstitial glucose response (mmol/L) according to experimental condition.

653 Exposure to the experimental solutions is centred at 0 minutes which represents time of
654 solution intake

655

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

658

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660

661

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