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Research report

Sweet delusion. Glucose drinks fail to counteract ego depletion ☆

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ABSTRACT

Initial acts of self-control have repeatedly been shown to reduce individuals' performance on a consecutive self-control task. In addition, sugar containing drinks have been demonstrated to counteract this so-called ego-depletion effect, both when being ingested and when merely being sensed in the oral cavity. However, since the underlying evidence is less compelling than suggested, replications are crucially required. In Experiment 1, 70 participants consumed a drink containing either sugar or a non-caloric sweetener between two administrations of delay-discounting tasks. Experiment 2 ($N = 115$) was designed to unravel the psychological function of oral glucose sensing by manipulating the temporal delay between a glucose mouth rinse and the administration of the consecutive self-control task. Despite applying powerful research designs, no effect of sugar sensing or ingestion on ego depletion could be detected. These findings add to previous challenges of the glucose model of self-control and highlight the need for independent replications.

Introduction

By overriding and inhibiting prepotent responses, impulses, thoughts and emotions (i.e., by exerting self-control), individuals are able to maximize their long-term best interests (Muraven & Baumeister, 2000). Abstaining from the immediate gratification associated with an additional piece of cake, for instance, provides the possibility to obtain the even larger, though more delayed rewards resulting from a healthy diet (Logue & King, 1991; Rachlin, 2004). Unfortunately, however, the capacity to exert self-control is crucially limited, a psychological phenomenon leading Baumeister and colleagues to coin the term *ego depletion* (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Muraven, Baumeister, & Tice, 1999). According to the strength model of self-control (Baumeister, Vohs, & Tice, 2007), all acts requiring self-control draw on a common resource and self-control performance is determined by the current level of this resource. Hence, individuals are expected to perform more poorly on a self-control task after their resource has been depleted by a previous self-control task (Muraven & Baumeister, 2000). This ego-depletion hypothesis has been subject to multiple empirical tests adopting the so-called dual-task paradigm (Hagger, Wood, Stiff, & Chatzisarantis, 2010). In this paradigm, participants in the experimental condition are asked to complete two consecutive tasks which are supposed to require self-control while for control participants, only the second of the two tasks taxes self-control capacities. As the finite mental self-control resource is thought to be more depleted in the experimental group than in the control group, control participants are expected to perform better on the second self-control task. In fact, a recent meta-analysis of 83 studies (Hagger et al., 2010) reported a medium-to-large effect size for the difference in self-control performance on a consecutive task between a depleted experimental group and a non-depleted control group.

Glucose consumption and ego depletion

Moreover, studies by Gailliot et al. (2007) suggested that self-control strength is more than a metaphorical resource by reporting that (a) initial acts of self-control reduce blood glucose levels, (b) decreased performance on a second self-control task is associated with decreases in blood glucose and (c) supplementing glucose, but not artificial sweetener, counteracts the ego-depletion effect. This latter finding has been replicated several times (DeWall, Baumeister, Gailliot, & Maner, 2008; Gailliot et al., 2009; Masicampo & Baumeister, 2008; Wang & Dvorak, 2010), leading Hagger et al. (2010) to conclude that there is "a large homogenous effect" (p. 514; $d = 0.75$) of experimental glucose administration on ego depletion. From a statistical point of view, however, the original results supporting a role for blood glucose in self-control (Gailliot et al., 2007) are highly incredible (Schimmack, 2012). In total, Gailliot et al. (2007) reported significant results for 9 studies

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Table 1
Characteristics of the studies investigating the effect of sugar supplementation on ego depletion included in the meta-analysis by Hagger et al. (2010).

Study	Depletion task	Dependent task	Dependent measures	Statistical test	*N* (reported)[a]	*N* (extracted)	*d* (reported)[b]	*d* (extracted)
Gailliot et al. (2007, study 8)	Writing about the own death	Completing word fragments	Number of unsolved word fragments ($M < 0.3$)	ANOVA	Approximately half of the total sample size of $N = 73$	**73**	0.55	0.55
Gailliot et al. (2007, study 9)	Completing an multiple-choice exam	Indicating the willingness to help in hypothetical scenarios	Standardized score of willingness to help	Student's *t*-test	18	18	1.57	1.57
De Wall et al. (2008, study 2)	Not attending to words displayed while watching a video	Indicating the willingness to help a stranger	Number of hours willing to help	Student's *t*-test	25	**30**	1.07	**0.96**
Masicampo and Baumeister (2008)	Not attending to words displayed while watching a video	Hypothetically choosing between two apartments while one of them is displayed next to a less attractive decoy option	Binary choice between the two options	ANOVA	67	**57**	0.42	**0.77**
Gailliot et al. (2009)	Scoring high on a questionnaire assessing the attitude towards homosexuals (HATH)	Writing about a typical day in the life of a homosexual	Number of prejudices used ($M = 0.78$), number of stereotypes expressed	Regression analysis	"those scoring 1 SD above the mean of the HATH" out of a total sample of $N = 51$	**51**	0.69 (for number of prejudices; second measure not significant)	0.69 (for number of prejudices; second measure not included)

Note: Bold indicates values extracted for the meta-analysis (Hagger et al., 2010) which deviate from the data reported in the original studies.
[a] Sample size is reported for the subgroup of depleted participants according to the aim of the meta-analysis (Hagger et al., 2010).
[b] Effect size was calculated or converted when necessary.

involving predominantly small sample sizes. Across these studies, effect sizes were strongly negatively correlated with sample sizes and total power (i.e. the probability to obtain only significant results) was less than 1% (Schimmack, 2012). Hence, in all probability the effect sizes reported by Gailliot et al. (2007) are inflated, potentially as a result of selective reporting of significant results.

In addition to this statistical criticism, a closer look on the five studies (total $N = 229$) included in the meta-analysis by Hagger et al. (2010) reveals several inconsistencies and methodological shortcomings (see Table 1):

(1) Hagger et al. (2010) extracted incorrect values for effect and/or sample sizes from four out of five studies, thereby overestimating the overall effect size. Moreover, with regard to the study by Gailliot, Michelle Peruche, Plant, and Baumeister (2009), only the effect of sugar consumption on one dependent variable (prejudices), but not on the other (stereotypes) was included in the meta-analysis. Notably, the experimental manipulation did not significantly affect the latter measure.
(2) Apparently, the dependent variables assessed in the studies by Gailliot et al. (2009) and Gailliot et al. (2007, study 8) are subject to floor effects. Especially when interpreting interaction effects, these floor effects pose a serious threat to the validity of an experiment due to a lack of variance in the outcome measure (Hessling, Schmidt, & Traxel, 2004).
(3) Some of the experimental paradigms applied in the original studies appear inadequate with regard to the purpose of this meta-analysis (i.e. testing the impact of glucose supplementation on the ego-depletion effect). Gailliot et al. (2009), for instance, did not use a depletion task at all. Instead, Hagger et al. (2010) reported the average effect of supplementation only for participants scoring high on a related trait measure arguing that "the individual difference variable served as the depletion condition" (p. 504). Interpreting such findings as support for a moderating role of glucose on the exhaustion of self-control resources is rather far-fetched and dangerous in enabling researchers to divide their samples in arbitrary groups and, subsequently, to choose the subsample which produces the desired effect. Furthermore, it appears highly speculative to assume that the expressed willingness to help a stranger in a hypothetical scenario (as in Gailliot et al., 2007, study 9) is an adequate measure of self-control in sensu Hagger et al. (2010), i.e. a task demanding "the effortful suppression of an impulse or overriding of a habitual or dominant response" (p. 499). In view of the large number of established behavioral self-control tasks (see Duckworth & Kern, 2011, for review), applying depletion tasks and dependent measures which are only remotely related to the construct of self-control (see Table 1) appears to be a peculiar choice in experimental design.

In sum, the original (Gailliot et al., 2007) and meta-analytic (Hagger et al., 2010) evidence is less compelling than suggested, illustrating that the effect of sugar supplementation on ego depletion is far from being an established research phenomenon. In view of this apparent lack of adequate and powerful studies, independent replications investigating the role of glucose for self-control are crucially required (Frank & Saxe, 2012; Simmons, Nelson, & Simonsohn, 2011). Importantly, as emphasized by Schimmack (2012), "replication studies with high power can provide strong evidence that original studies produced inflated effect sizes" (p. 14). Wang and Dvorak (2010) presented a first example of such a powerful replication by conducting a repeated measurement experiment involving a prototypical self-control task (delay discounting), thereby generating the first evidence for the effect of sugar consumption on ego depletion outside the research group of Baumeister and colleagues. In the same vein, the present study attempted to scrutinize this effect by benefiting from the power advantages associated with repeated measurements within a delay discounting paradigm (Experiment 1). However, since the measure of delay discounting administered by Wang and Dvorak (2010) showed low test–retest reliability, a more reliable version of the same task was used to decrease the influence of error variance.

Oral glucose sensing and ego depletion

Recently, the metabolic explanation for an effect of oral sugar administration on ego depletion (i.e., the glucose model of self-control; Gailliot et al., 2007) has had to face serious challenges. First, by reanalyzing the original data provided by Gailliot et al. (2007), Kurzban (2010) demonstrated that peripheral blood glucose is not reduced by an initial self-control task. Moreover, from a physiological perspective, human brain functioning has been concluded to be unlikely to be impaired by the negligible amount of glucose consumed during self-control tasks (Kurzban, 2010; see also Beedie & Lane, 2012). Second, regarding the claim that blood glucose levels predict task performance on a second self-control task in ego-depleted individuals (Gailliot et al., 2007), a powerful but non-significant replication study (Dvorak & Simons, 2009) indicated that the large effects reported in the original article are likely to be overestimated (Schimmack, 2012). Third, an increasing body of evidence suggests that merely rinsing one's mouth with glucose solution is sufficient to counteract ego depletion (Hagger & Chatzisarantis, 2012; Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012), thereby yielding an average effect size comparable to the one reported for the effect of drinking glucose ($d = 0.80$, see Table 2, and the Discussion section of Experiment 2 for an analysis of the effect's statistical credibility). These findings appear to be in line with evidence from exercise physiology indicating that carbohydrate mouth rinse has a positive effect on endurance time trial performance (Carter, Jeukendrup, & Jones, 2004; Chambers, Bridge, & Jones, 2009; Pottier, Bouckaert, Gilis, Roels, & Derave, 2010; Rollo, Cole, Miller, & Williams, 2010, see also Painelli, Nicastro, & Lancha, 2010, for review). The observed improvements in running and cycling performance have been attributed to the activation of reward-processing dopaminergic pathways in the ventral striatum via oral receptors sensitive to glucose (Carter et al., 2004; Chambers et al., 2009). As a consequence, glucose perception is proposed to affect both physical exercise performance and mental self-control performance by altering the motivational status of depleted individuals (Hagger & Chatzisarantis, 2012; Inzlicht & Schmeichel, 2012; Kurzban, 2010; Molden et al., 2012). However, while critics of the metabolic account agree that glucose functions as a motivational input furthering persistence on cognitive or physical tasks (rather than as a physiological constraint), it is still unclear how and why self-control performance is affected by this input. In other words, the psychological function of sensing glucose in the oral cavity remains to be elucidated.

On the one hand, sensing glucose might act as a reward following the exertion of self-control on an initial task (Hagger & Chatzisarantis, 2012). Importantly, as stressed by Inzlicht and Schmeichel (2012), ego-depleted participants typically do not receive any reinforcement for being self-controlled on the first task. Unless they are provided with some reward after this task (e.g., in form of sugar sensing), their motivation may shift in a way that they prefer more impulsive behavioral strategies on a second self-control task (Inzlicht & Schmeichel, 2012).

On the other hand, sensing sugar in the oral cavity might function as a discriminative stimulus (Skinner, 1938) influencing the choice between self-controlled and impulsive behavioral strategies by signaling behavior–environment contingencies (Rachlin, 2004) or, as paraphrased by Kurzban (2010), by altering "the representation of costs and benefits of continuing [to exert self-control]" (p. 255). From the perspective of a depleted individual (i.e., an individual that has learned that being self-controlled does not pay off), sensing sugar may indicate the availability of resources in the environment and, hence, signal that future-oriented or self-controlled actions are affordable in the present context (see also Wang & Dvorak, 2010, for a comparable account). Note that these two explanations can be dissociated by their temporal relationships to the behavior of interest (i.e., the performance on a second self-control task). While a reward acts retrospectively by reinforcing the choice of a self-controlled strategy on a first task, a discriminative stimulus prospectively signals which strategy is likely to be most beneficial under the current circumstances. Hence, manipulating the contiguity between sugar administration and the two self-control tasks within a dual-task paradigm might contribute to clarify the role of glucose in ego depletion. To this end, Experiment 2 compared the effects of ego depletion on highly reliable measures of response inhibition and interference suppression across groups of individuals that rinsed their mouth with a glucose solution (a) directly after the depletion task, (b) directly before the second self-control task, (c) on both occasions or (d) on none of these occasions. As a further control, a fifth group was included that ingested the glucose solution on both occasions, thereby allowing for comparisons with previous studies investigating the effect of carbohydrate rinsing on self-control (Molden et al., 2012).

General methods

During both experiments, the experimenter was present in the laboratory but separated from the participant by means of a wall in the middle of the room. Experimental tasks were designed using OpenSesame 0.24 (Mathôt, Schreij, & Theeuwes, 2012) and

Table 2
Meta-analysis across the studies investigating the effect of rinsing glucose on ego depletion.

	N in depletion condition	Effect size	Effect size in *d*	Power with $d = 0.75$[a]
Hagger and Chatzisarantis (2012)				
Study 1	27	$\eta_p^2 = .26$	1.19	.47
Study 2	32	$\eta_p^2 = .17$	0.91	.54
Study 3	34	$\eta_p^2 = .11$	0.70	.56
Study 4[b]	23	$\eta_p^2 = .41$	1.67	.40
Study 5	20	$\eta_p^2 = .13$	0.77	.36
Total	136		1.02	.02
Molden et al. (2012)				
Study 2	22	$d = 0.63$	0.63	.39
Study 3	30	$d = 0.73$	0.73	.51
Total	52		0.69	.20
Sanders, Shirk, Burgin, and Martin (2012)	51	$d = 0.31$	0.31	.84
Total	239		0.80	.003

[a] Power was calculated based on the average effect size reported for the influence of drinking glucose (Hagger et al., 2010), as this is logically the largest effect the authors conducting the original studies could have assumed.
[b] Only $N = 45$ for the total sample (depletion and non-depletion condition) is reported.

presented on a 24 inch flat screen (Samsung, Seoul, South Korea). Demographic information questionnaires and personality scales (e.g., BFI-10, Rammstedt & John, 2007; BIS-11, Patton & Stanford, 1995, German translation by Preuss et al., 2007) were used as filling questionnaires.

Statistical analyses were performed using SPSS 20.0 (IBM, Armonk, NY). The level of significance was set at $\alpha = .05$. Statistical power was estimated using G*Power 3.1.5 (Faul, Erdfelder, Lang, & Buchner, 2007).

Experiment 1

Experiment 1 was designed to replicate the counteracting effect of sugar consumption on ego depletion (Gailliot et al., 2007; Hagger et al., 2010). Following the protocol of Wang and Dvorak (2010), participants' delay-discounting rates were assessed prior and after the consumption of a sweet drink containing either sugar or artificial sweetener.

Methods

Participants

A total of 70 undergraduate students (62 female) participated for course credit, which was not contingent on performance. Participants' age ranged from 18 to 32 years ($M = 21.80$ years, SD = 2.58 years). Participants were instructed not to eat for 1.5 h prior to their arrival at the laboratory.

Experimental tasks

By means of an initial selective attention task (SA), a priori state differences in a potential resource of self-control strength should be reduced before the beginning of the actual experiment. The task was closely modeled to the classic Ebbinghaus illusion (see for instance Roberts, Harris, & Yates, 2005) forcing participants to judge (by pressing one of two keys) whether an isolated probe stimulus (a gray circle) or a target stimulus (a circle varying in color from red to green) surrounded by five inducers (gray circles) appeared larger. In order to adequately judge the relative size of the stimuli, participants had to selectively attend the relevant stimulus dimension (i.e. the actual size of the target) while ignoring irrelevant dimensions (i.e. inducer size and target color).

Individuals' tendency to discount delayed rewards was assessed by means of a computerized choice procedure forcing participants to state a preference between two simultaneously displayed monetary rewards (Rachlin, Raineri, & Cross, 1991). Across trials, participants hypothetically chose between a large delayed (one week to 50 years) reward of 1000€ and a smaller immediate reward (100–990€). In order to enable repeated measurements of delay discounting (Wang & Dvorak, 2010), two sets of trials involving different delays were developed (DD1, DD2). Delays were randomly assigned to the two trial sets with three delays being represented in both sets, but expressed in different temporal units (DD1: 4 weeks, 2 months, 3 months, 4, months, 5 months, half a year, 9 months, 12 months; DD2: 1 week, 2 weeks, 1 month, 6 months, 1 year, 5 years, 10 years, 25 years, 50 years). For each delay, indifference points (i.e. the subjective values of the delayed reward) were determined as the average between the largest rejected and the smallest accepted immediate reward. Fitting Mazur's formula of hyperbolic delay discounting (Mazur, 1988) to these indifference points using a nonlinear curve-fitting program (OriginPro 8.6, OriginLab Corporation, Northampton, MA, USA) yielded estimates of individual discounting rates (k). In order to normalize the resulting sample distribution, k values were natural-log transformed. Note that in contrast to Wang and Dvorak (2010), a different delay-discounting task was applied since the k values computed from the two trial blocks (consisting of seven choices each) administered in the original study showed low test–retest reliability ($r_{T1,T2} = .49$; X.T. Wang, personal communication, January 21, 2013). Discounting parameters obtained from the more extensive choice procedure introduced by Rachlin et al. (1991), however, were demonstrated to be highly reliable across experimental sessions ($r_{T1,T2} = .91$; Simpson & Vuchinich, 2000). Hence, for the present study, the experimental task was designed according to the latter approach, presenting immediate reward sizes in ascending order for each delay condition.

Procedure and design

Prior to arrival at the laboratory, participants were randomly assigned to one of two conditions (experimental group: 30 females, 5 males; control group: 32 females, 3 males). After entering the laboratory, they completed informed consent forms before their initial blood glucose level (T_1) was assessed (Contour® XT meter, Bayer AG, Leverkusen, Germany). Subsequently, they completed the selective attention task (SA, 528 trials) as well as the first 184 trials of delay discounting (DD1). Depending on condition, participants then consumed 250 ml of caffeine-free soda, which contained either sugar (7 Up®; experimental condition) or an artificial sweetener (7 Up light®; control condition) while being blind to group allocation (due to practical reasons and in accordance with Wang and Dvorak (2010), only the participants, but not the experimenters were unaware of type of soda). After consumption, they rated the pleasantness of the soda as well as their current state of hunger and exhaustion on an 11-point Likert scale. In order to allow the sugar from the drink to be metabolized (Gailliot et al., 2007), participants then completed filling questionnaires for an interval of 10–15 min. Following the second assessment of blood glucose (T_2), another 207 trials of delay-discounting (DD2) were administered. Note that this dual-task paradigm replicates the procedure applied by Wang and Dvorak (2010) by using delay discounting as both, depletion task (DD1) and dependent measure (DD2).

Data analysis

A 2×2 ANOVA was conducted with repeated measurements of log-transformed discounting parameters (DD1 vs. DD2) as within-subject factor and condition (experimental vs. control) as between-subject factor. A significant interaction between the two factors would reflect an effect of sugar consumption on ego depletion (Wang & Dvorak, 2010).

Results

Experimental and control group did not differ with respect to gender distribution (86% vs. 91% female; $p = .71$) or any of the self-reported state, trait or demographic variables presented in Table 3 with the exception of the rating of the soda's pleasantness ($t(68) = 2.19$, $p = .03$, all other $p > .05$). Similarly, there was no group difference in initial blood glucose level ($t(68) = 0.18$, $p = .86$). However, the mean blood glucose level at T_2 was significantly higher in individuals having consumed a sugar-containing drink as compared to participants who received a sweet placebo ($t(68) = 6.41$, $p < .05$), indicating that the experimental manipulation was successful. Note that the group difference in blood glucose at T_2 is entirely attributable to a substantial increase in the experimental group ($t(34) = 9.20$, $p < .05$), whereas mean blood glucose level in the control group did not change significantly from T_1 to T_2 ($t(34) = 0.13$, $p = .90$).

Along the lines of blood glucose at T_2, there was a significant group difference in DD2 performance ($t(68) = 2.18$, $p < .05$). Log-transformed k values were higher (i.e. discounting of delayed rewards was steeper) in control participants than in the

Table 3
Group means, SDs and differences on demographic, psychometric, behavioral and state variables for Experiment 1 ($N = 70$).

Measure	Experimental group		Control group		*d*
	M	SD	*M*	SD	
Personal characteristics					
Age (years)	21.80	2.22	21.79	2.94	0.00
BMI (kg/m^2)	21.79	3.08	21.46	2.61	0.11
Income (€)	600.03	198.94	619.71	279.33	−0.08
BFI-10 average scores (range: 1–5)					
Extraversion	3.69	0.91	3.41	1.09	0.27
Neuroticism	2.99	0.94	2.94	1.00	0.04
Conscientiousness	3.77	0.77	3.69	0.84	0.10
Agreeableness	3.29	0.78	3.20	0.95	0.10
Openness	3.69	1.13	3.86	0.86	−0.17
BIS-11 average scores (range: 1–4)					
Cognitive complexity	2.21	0.40	2.15	0.49	0.13
Perseveration	1.68	0.47	1.70	0.59	−0.04
Cognitive instability	1.94	0.51	2.15	0.58	−0.38
Self-control	1.94	0.44	1.92	0.52	0.05
Motor impulsiveness	2.11	0.42	2.07	0.45	0.11
Attention	1.86	0.46	1.95	0.52	−0.20
Total	1.98	0.32	1.99	0.36	−0.04
State variables					
Blood glucose (mg/dl) T_1	99.74	33.91	98.63	16.52	0.04
Blood glucose (mg/dl) T_2	131.77	26.03	98.34	16.60	1.53*
Pleasantness	6.97	1.36	5.89	2.60	0.52*
Hunger	3.63	2.62	3.40	2.57	0.09
Exhaustion	5.00	2.06	4.14	2.13	0.41
Behavioral tasks					
SA_errors	59.11	22.48	52.40	16.28	0.34
DD1_log[*k*]	−7.65	1.22	−6.84	1.50	−0.60*
DD2_log[*k*]	−7.71	0.89	−7.11	1.36	−0.52*

Note: BIS-11 = Barratt Impulsiveness Scale, BFI-10 = Big Five Inventory, SA = selective attention task, DD = delay-discounting task.
d = Standardized mean difference experimental group – control group.
* $p < .05$.

experimental group. However, Fig. 1 suggests that this might be due to an a priori group difference on this measure. This notion is supported by a 2 × 2 ANOVA (control group vs. experimental group × DD1 vs. DD2) revealing that sugar consumption did not affect ego depletion (i.e. the interaction is not significant, $F(1,68) = 1.12$, $p = .29$, $\eta_p^2 = .02$). DD1 and DD2 scores were highly correlated ($r = .80$) indicating good test–retest reliability. Given this correlation, a sample size of $N = 70$ and a significance level of $\alpha = .05$, an effect of glucose consumption on ego depletion as large as reported by Hagger et al. (2010) ($d = 0.75 \triangleq \eta_p^2 = .12$) or Wang and Dvorak (2010) ($\eta_p^2 = .21$) could have been detected with a probability close to 1 ($1 - \beta > .99$). Both of these originally reported effect sizes are not included within the 95% confidence interval of the effect size found in this study [.00,.11]. Notably, sensitivity analysis demonstrated that the present design still yielded 95% statistical power assuming an effect size of $d = 0.28$ and even effects as small as $d = 0.21$ could have been detected with sufficient power ($1 - \beta = .8$).

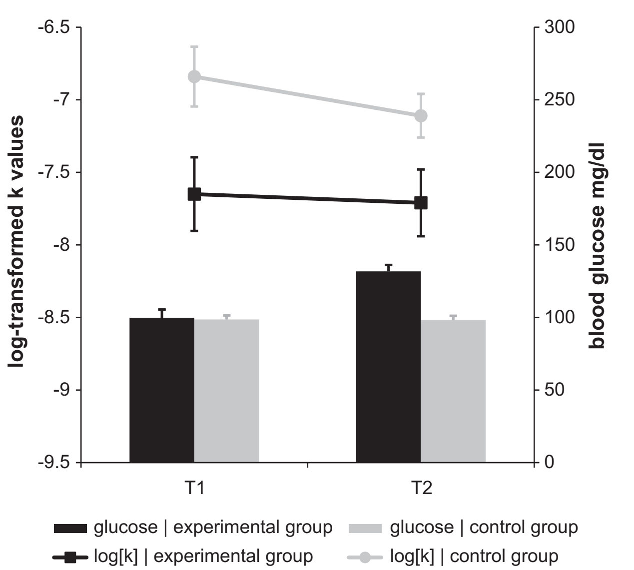

Fig. 1. Mean delay-discounting rates and blood glucose levels as functions of group assignment and timing relative to sugar consumption in Experiment 1. Participants in the experimental group received a soft drink containing sugar whereas members of the control group were administered a soft drink that contained artificial sweetener. Higher values of log[*k*] indicate steeper discounting of delayed rewards (i.e. less self-control). Error bars represent standard error of the mean.

Discussion

Although participants had to complete 528 trials on the selective attention task and 184 trials of delay discounting between the first two assessments of blood glucose, the mean blood sugar level in the control group did not decrease. This finding supports the argument of Kurzban (2010) and Molden et al. (2012) who demonstrated that performing a self-control task is unlikely to lower peripheral blood glucose levels (as argued by Gailliot et al., 2007).

In addition, the applied dual-task paradigm replicating the experiment conducted by Wang and Dvorak (2010) did not reveal a significant effect of sugar administration on the exhaustion of self-control resources, a finding which is also inconsistent with the results obtained by Gailliot, Baumeister and colleagues (DeWall et al., 2008; Gailliot et al., 2007, 2009; Masicampo &

Baumeister, 2008). Statistical power analysis indicated that the present research design was highly sensitive to detect an effect as large as described by Wang and Dvorak (2010) or Hagger et al. (2010). Hence, given the present data, the probability of a Type II error is negligibly low, indicating that there is no "large and homogeneous effect" (Hagger et al., 2010, p. 514) of sugar consumption on ego depletion.

Unfortunately, the two groups of participants were not matched with regard to their performance on the initial delay-discounting task. While this might be regarded as a limitation of this experiment, it illustrates above all the use of repeated measures in between-group designs. Without having access to the information from the initial delay-discounting task, one would have had to attribute the group difference in DD2 performance to the experimental manipulation. As nicely demonstrated by this case, random group assignment does not automatically eliminate potential confounding variables (Krause & Howard, 2003). Hence, by increasingly using repeated measures designs which naturally control for imperfect randomization, the validity of experiments could clearly be enhanced, not only in the field of ego depletion.

Moreover, in view of the high test–retest reliability of the hypothetical choice procedure applied in this study, one may be led to the conclusion that the analyzed measure of delay discounting was too stable to be sensitive to changes. However, obtaining a large correlation between measures administered before and after an intervention does not imply that the measure has not been altered by the intervention. It just indicates that the measure has been altered *in a similar way* for every participant, while low test–retest reliability implies that the measure is fluctuating in an unsystematic way. Hence, in contrast to the small number of choice items used by Wang and Dvorak (2010), the applied measure of delay discounting is less susceptible to changes which are simply produced by error variance but *more sensitive* to changes which are actually caused by the treatment. In a similar vein, it may be argued that it is rather unrealistic to expect a basic human trait like the valuation of future consequences to be changed by an intervention like glucose administration. Note, however, that this is essentially what has been claimed by studies reporting sugar effects on delay discounting (Wang & Dvorak, 2010), the willingness to help strangers (Gailliot et al., 2007) or the attitude towards homosexuals (Gailliot et al., 2009). Hence, the observation of pre–post changes in delay-discounting performance which are invariant across experimental conditions illustrates that previous studies have been too optimistic regarding the potential of sugar drinks to alter ego depletion.

Experiment 2

Experiment 2 was designed to unravel the psychological function of sensing glucose in the oral cavity within the context of ego depletion. As hypothesized above, the perception of sugar might influence the performance on a second self-control task via two different ways: (a) by retrospectively reinforcing the choice of a self-controlled strategy on a first task or (b) by prospectively signaling which strategy is likely to be most beneficial under the current circumstances. While these functions are not mutually exclusive, independently manipulating the solution rinsed directly after the first self-control task (i.e., the *reward drink*) and the solution rinsed directly before the second self-control task (i.e., the *signal drink*) allowed assessing their differential contributions to the reported effect of oral sugar sensing on ego depletion (Hagger & Chatzisarantis, 2012; Molden et al., 2012). Furthermore, by including an experimental group whose members drank the glucose solution at both occasions, it was possible to compare the effect of oral glucose sensing with the one of glucose ingestion.

Methods

Participants

115 undergraduate students (103 female; mean age = 21.80; SD = 3.78) participated for course credit, which was not contingent on performance. Participants were instructed not to eat for 2 h prior to their arrival at the laboratory.

Experimental task

Distractors varying in their degree of compatibility with the target were added to a classic go/no-go task (GNG; e.g., Eigsti et al., 2006) to allow for the simultaneous assessment of two partly distinct facets of self-control: response inhibition and interference suppression (Brydges et al., 2012). Participants were required to respond (press the space bar) as fast as possible whenever a frequent go stimulus (red circle, frequency: 80%) appeared in the center of the computer screen, but to withhold responses to infrequent no-go stimuli (green circle, frequency: 20%) for 1500 ms. During 75 initial training trials, participants instrumentally learned about task contingencies via visual and auditory feedback. During 450 subsequent test trials, only negative auditory feedback was provided after misses (not responding to a go stimulus within 1500 ms) and false alarms (responding to a no-go stimulus). Between trials, a fixation cross was presented for 600 ms (inter-trial interval, ITI) in the center of the display. Establishing a presentation ratio (go vs. no-go) of 4:1 and an "unnatural" stimulus–response mapping (red = go; green = no-go) forced participants to inhibit prepotent go responses when confronted with an infrequent no-go stimulus. Hence, the number of false alarms (or errors of commission) served as a measure of response inhibition (Reynolds, Ortengren, Richards, & de Wit, 2006). In addition, four task-irrelevant distractors (circles varying in color from red to green [hue_{HSL} = 0–120°]) were configured around the central target stimulus. The reaction time (RT) difference between incompatible (red target surrounded by green distractors) and compatible (red target surrounded by red distractors) go trials (i.e., the RT compatibility effect) was analyzed as a measure of interference suppression.

Procedure and design

Prior to arrival at the laboratory, participants were randomly assigned to one of five conditions: glucose–glucose (GG; 19 female, 4 male), glucose–stevia (GS; 19 female, 4 male), stevia–glucose (SG; 22 female, 1 male), stevia–stevia (SS; 22 female, 1 male), and drinking glucose (DG; 21 female, 2 male). After having provided informed consent, all participants completed the experimental task for the first time (depletion task; GNG1). With exception of the DG group, participants were then asked to rinse their mouth with some of the solution (100 ml) provided in a drinking glass for 10 s and to spit it back into the cup afterwards. The volume of the solution was measured before and after rinsing to ensure that participants did not ingest any of the solution (Hagger & Chatzisarantis, 2012). Participants in the GG and GS group were provided with an 18% glucose solution whereas participants assigned to the PS and SS condition rinsed their mouth with a non-caloric placebo solution (stevia) matched in sweetness (reward drink). Subsequently, participants completed a set of filling questionnaires for an average of 26.30 min (SD = 6.42) before they received another cup of rinsing solution. This time, participants in the GG and SG condition were asked to rinse their mouth with glucose whereas the GS and SS group were provided with the artificially sweetened solution (signal drink). Participants assigned to the DG group were asked to drink 100 ml of the glucose solution at both occasions (i.e., as a reward drink and as a signal drink). Finally, all participants engaged in the experimental task for a second time (dependent task; GNG2) before they were debriefed, thanked and dismissed.

Participants rated both the signal and the reward drink for sweetness and pleasantness on an 11-point Likert scale. Both the experimenter and the participant were blind to condition.

Data analysis

Two $2 \times 2 \times 2$ ANOVAs were conducted with repeated measurements (GNG1 vs. GNG2) of false alarms and compatibility effect, respectively, as within-subject factor and reward drink (glucose vs. stevia) and signal drink (glucose vs. stevia) as between-subject factors. A significant interaction between the within-subject factor and one or both of the between-subject factors would indicate an effect of glucose rinsing on ego depletion. While a significant interaction with reward drink would suggest that the main function of glucose sensing is a reinforcing one, a significant interaction with signal drink would lend support to the hypothesis that the perception of glucose functions as a discriminative stimulus.

Moreover, for each of the dependent variables, two interaction contrasts were calculated to examine whether potential changes in these measures (from GNG1 to GNG2) differ between (a) the DG group and the GG group and (b) the DG group and the SS group. The former analysis allows examining whether drinking and rinsing glucose affect ego depletion to a different extent while the latter one was conducted to investigate whether glucose consumption affects ego depletion at all.

Results

Experimental groups did not differ with respect to gender distribution or any of the self-reported state, trait or demographic variables presented in Table 4 with the exception of the BIS subscale perseverance ($F(1,110) = 2.92$, $p = .03$; all other $ps > .05$). A significant within-subject effect was found for both measures of self-control, the number of false alarms ($F(1,88) = 6.01$, $p < .05$, $\eta_p^2 = .06$) and the magnitude of the compatibility effect ($F(1,88) = 11.58$, $p < .05$, $\eta_p^2 = .12$), with both measures increasing from T1 to T2 (see also Fig. 2). No other main effects or interactions in the $2 \times 2 \times 2$ ANOVAs approached significance (all $F < 1$, all $\eta_p^2 < .005$). With regard to the contrast between the DG and GG group, neither the T1–T2 increase in false alarms ($F(1,110) = 0.01$, $p = .93$) nor the one in the magnitude of the compatibility effect ($F(1,110) = 3.12$, $p = .08$) were attenuated by ingesting glucose as compared to merely rinsing with glucose solution. Note that, instead, the trend of an influence on the latter variable is due to the ego depletion effect being most pronounced in the GG group (see also Fig. 2). Similarly, with regard to the contrast between the DG and SS group, neither the pre–post difference in false alarms ($F(1,110) = 0.05$, $p = .82$) nor the one in compatibility effect ($F(1,110) = 1.10$, $p = .30$) were moderated by group assignment indicating that drinking glucose did not counteract ego depletion to a different extent than merely rinsing with a placebo solution.

The number of false alarms ($r_{GNG1,GNG2} = .76$) as well as the magnitude of the compatibility effect ($r_{GNG1,GNG2} = .50$) were highly correlated across measurements. Given these correlations and a

Table 4
Group means and SDs on demographic, psychometric, behavioral and state variables for Experiment 2 ($N = 115$).

	GG		GS		SG		SS		DG	
	M	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
Personal characteristics										
Age (years)	21.52	3.17	23.13	4.98	21.52	3.57	21.30	3.08	21.52	3.84
BMI (kg/m^2)	22.10	2.83	21.90	4.85	22.07	4.04	21.09	2.22	23.32	4.46
Income (€)	643.04	608.30	616.52	212.57	657.39	368.34	533.48	237.63	524.78	231.32
NEO-FFI average scores (range: 1–5)										
Extraversion	3.60	0.48	3.61	0.58	3.51	0.37	3.42	0.43	3.69	0.41
Neuroticism	2.53	0.56	2.55	0.61	2.80	0.67	2.82	0.72	2.81	0.67
Conscientiousness	3.86	0.55	3.73	0.53	3.57	0.41	3.72	0.59	3.87	0.43
Agreeableness	3.95	0.32	3.85	0.59	3.78	0.48	3.91	0.59	3.89	0.40
Openness	3.83	0.54	3.79	0.56	3.69	0.40	3.66	0.47	3.62	0.60
BIS-11 average scores (range: 1–4)										
Cognitive complexity	2.23	0.39	2.19	0.43	2.08	0.37	2.17	0.43	2.19	0.51
Perseverance	1.74	0.44	2.00	0.43	1.87	0.46	1.86	0.52	1.54	0.46
Cognitive instability	2.09	0.43	2.18	0.45	1.97	0.40	2.04	0.68	1.94	0.38
Self-control	1.83	0.41	2.13	0.63	2.00	0.41	1.98	0.45	1.86	0.45
Motor impulsiveness	2.11	0.48	2.19	0.52	2.05	0.38	2.09	0.41	2.08	0.45
Attention	1.78	0.34	1.95	0.50	1.96	0.38	2.04	0.49	1.90	0.43
Total	1.97	0.24	2.11	0.36	2.00	0.24	2.04	0.33	1.94	0.30
State variables										
Pleasantness T1	4.39	2.06	4.09	2.21	4.04	1.87	4.17	2.46	4.04	2.08
Sweetness T1	7.39	0.89	8.13	0.97	7.48	1.34	7.70	1.61	8.04	1.30
Hunger T1	4.65	2.12	4.91	2.97	4.39	3.23	3.57	2.76	4.35	2.37
Exhaustion T1	4.83	2.10	5.39	1.78	5.17	2.10	5.09	1.73	5.26	2.14
Pleasentness T2	4.00	2.32	3.39	2.55	4.61	1.90	4.05	2.61	3.59	2.30
Sweetness T2	7.35	1.03	7.70	1.69	6.83	1.44	7.36	1.71	8.14	1.39
Hunger T2	4.52	2.43	4.70	2.93	4.57	2.97	3.68	2.61	4.77	2.49
Exhaustion T2	5.22	1.70	5.26	1.63	4.91	2.00	5.45	2.04	5.23	2.25
Behavioral measures										
GNG1_Median_RT_hit	429.59	36.85	422.98	51.31	412.35	43.74	431.76	53.87	419.80	67.49
GNG1_N_false_alarm	4.70	4.05	5.57	3.59	6.00	6.23	5.96	5.25	5.83	4.11
GNG1_compatibility_effect	35.52	33.45	23.89	34.72	29.11	28.47	28.52	32.23	23.50	31.54
GNG2_Median_RT_hit	414.50	42.90	413.57	80.68	398.33	44.38	410.70	40.57	407.87	45.83
GNG2_N_false_alarm	5.65	3.74	7.04	6.68	6.78	6.37	6.74	6.64	6.87	5.36
GNG2_compatibility_effect	40.96	31.40	34.80	26.44	39.50	15.93	40.04	22.63	43.89	17.46

Note: BIS-11 = Barratt Impulsiveness Scale, NEO-FFI = NEO Five-Factor Inventory, GNG = go/no-go task.

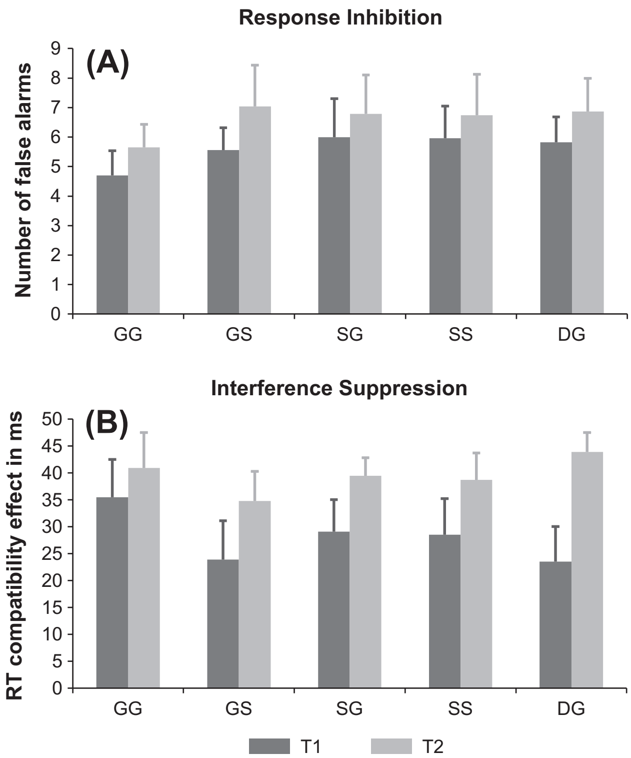

Fig. 2. Self-control performance as a function of group assignment and timing relative to glucose rinsing or consumption in Experiment 2. Participants rinsed their mouth with a glucose solution directly after the depletion task at T1 (GS), directly before the second self-control task at T2 (SG), on both occasions (GG), or on none of these occasions (SS). Participants in the DG condition drank glucose solution on both occasions. Higher numbers of false alarms (panel A) and higher RT differences between incompatible and compatible conditions (i.e., larger RT compatibility effects) indicate less self-controlled (more impulsive) performances.

significance level of $\alpha = .05$, an effect of the previously reported size ($d = 0.75$, Hagger et al., 2010; $d = 0.80$, see Table 2) could have been detected with a probability close to 1 ($1 - \beta > .99$) in both, the $2 \times 2 \times 2$ ANOVAs and the planned interaction contrasts. Sensitivity analysis demonstrated that the ANOVA still yielded 95% statistical power assuming effect sizes of $d = 0.31$ (false alarms) and $d = 0.44$ (compatibility effect), respectively. Even effects as small as $d = 0.24$ and $d = 0.35$, respectively, could have been detected with sufficient power ($1 - \beta = .8$). Smallest detectable effects for interaction contrasts are $d = 0.37$ (false alarms) and $d = 0.54$ (compatibility effect) for 95% power and $d = 0.29$ (false alarms) and $d = .42$ (compatibility effect) for 80% power, respectively.

Discussion

Rinsing one's mouth with glucose solution did not significantly alter ego depletion, neither when the solution was provided directly after the depletion task (reward drink), nor when it was provided directly before the second self-control task (signal drink). Hence, this experiment did not generate any evidence that sensing glucose in the oral cavity serves one of the two hypothesized psychological functions. Importantly, this implies that, despite applying a powerful research design, the present study could not replicate the findings presented by Hagger and Chatzisarantis (2012), Molden et al. (2012) and Sanders et al. (2012). Along the lines of Experiment 1, these results strongly suggest that the effect sizes reported in the original studies are substantially inflated (Schimmack, 2012). This suggestion receives further confirmation by analyzing the statistical credibility of the multiple study article published by Hagger and Chatzisarantis (2012). As illustrated by Table 2, the probability of obtaining a pattern as reported by these authors (i.e., only significant results in five underpowered studies) is only 2%, indicating that their findings rely either on luck or the selective reporting of positive results (Schimmack, 2012). Including the present results in a meta-analysis estimating the average effect of rinsing with glucose vs. artificial sweetener would yield a substantially smaller average effect size ($d = 0.43$). However, as this analysis would still include effect sizes which are likely to be inflated, meta-analytic calculations cannot provide a reliable estimate of the true effect size. Especially when the true effect size approaches zero, the results of such a meta-analysis can be very misleading (Bradley & Gupta, 1997).

Even more crucially, as the pre–post change in self-control performance did not differ between the DG group (who ingested glucose) and the SS group (who rinsed with stevia), the present study reports a second failed attempt to replicate the counteracting effect of sugar consumption on ego depletion (Gailliot et al., 2007; Hagger et al., 2010). Extending the meta-analysis by Hagger et al. (2010) to include the present findings would result in an average effect size of $d = 0.48$, a value which is still likely to be inflated (see above). To conclude, as the change in response inhibition and interference suppression, respectively, from T1 to T2 proved to be invariant across experimental groups, ego depletion can be assumed to be largely invariant to both, glucose sensing and glucose ingestion.

General discussion

Implications for research on ego depletion

Two experimental designs involving highly reliable, prototypical self-control tasks and yielding more than sufficient power failed to replicate the previously reported effects of glucose ingestion (Gailliot et al., 2007; Hagger et al., 2010) and glucose sensing (Hagger & Chatzisarantis, 2012; Molden et al., 2012). The studies supporting the idea that sugar administration counteracts ego depletion, on the other hand, could be demonstrated to be statistically incredible (Schimmack, 2012; Table 2) and methodologically problematic (see Table 1) implying that the notion of self-control relying on glucose as a limited physiological resource lacks empirical support. As a corollary, it is impossible to estimate reasonable average effect sizes in the context of a meta-analysis. In view of this apparent lack of adequate and powerful studies on the effect of sugar on ego depletion, future replications are crucially required. Further research investigating this phenomenon should (a) take a step back and concentrate on the effect of drinking glucose solution (as this is a logical prerequisite for an effect of glucose sensing) and (b) focus again on established tasks of self-control and inhibition (see, for instance, Duckworth & Kern, 2011). Applying unorthodox depletion tasks (like scoring high on a questionnaire assessing the attitude toward homosexuals; Gailliot et al., 2009) or dependent measures (like the self-reported willingness to help a stranger; Gailliot et al., 2007, study 9) should be abandoned to avoid the appearance of arbitrariness.

Implications for the understanding of self-control

In line with an increasing body of evidence demonstrating that (a) exerting self-control is unlikely to reduce blood glucose levels (Kurzban, 2010; Molden et al., 2012), and (b) performance on a second self-control task does not vary as a function of participants' blood glucose levels (Dvorak & Simons, 2009; Schimmack, 2012), the present results question the validity of the glucose model of self-control. Especially in view of the above-mentioned shortcomings of studies supporting the role of blood glucose in ego depletion, the model's major strength appears to lie in its ostensible support for "the folk notion of willpower" (Gailliot & Baumeister, 2007, p. 304) and not in its empirical corroboration. Moreover, a resource model of self-control strength might be inappropriate in general given its "protean" (Kurzban, 2010, p. 255) and unspecific nature (see also Kurzban, Duckworth, Kable, & Myers, 2013, for a more detailed critique of the strenght model). The fact that most of the tasks applied to validate the strength model could as well be conceived as reflecting general executive functioning (Miyake et al., 2000; Stuss & Alexander, 2007), for instance, has been accommodated by postulating that executive functions might subserve mechanisms of self-control (Hofmann, Schmeichel, & Baddeley, 2012). As a consequence, studies demonstrating a relationship between cognitive (or executive) demand and glucose consumption (e.g., Benton, Owens, & Parker, 1994; Scholey, Harper, & Kennedy, 2001) have been cited as supporting evidence. Likewise, changes in mood or arousal have been ruled out as alternative explanations for a link between glucose and self-control capacities by interpreting them as potential mediators (Gailliot & Baumeister, 2007).

Importantly, since it is highly questionable that fluctuations in blood glucose account for differences in the capacity to exert self-control, preventive strategies designed to counteract impulsive behavior should not rely on ideas which imply fuelling this resource (e.g. by means of complex carbohydrates; Gailliot et al., 2007; or by frequently eating small meals; Hagger, Wood, Stiff, & Chatzisarantis, 2009). Along similar lines, believing that sugar sensing in the oral cavity could boost the self-control abilities of depleted individuals by about a standard deviation (Hagger & Chatzisarantis, 2012) seems to be unjustified and might result in a distorted view of the construct of self-control.

Implications for scientific practice

When testing hypotheses, false-positives (i.e. erroneously rejecting the null hypothesis) may be the most costly errors scientists can make (Simmons et al., 2011). In order to minimize the risk of future experiments, theoretical considerations and practical implementations to rely on such Type I errors, independent replications are indispensable (Frank & Saxe, 2012). The present study was designed to comply with the widespread call for replications by applying study protocols reported to results in substantial effects of sugar consumption (Gailliot et al., 2007; Wang & Dvorak, 2010) and sugar sensing (Hagger & Chatzisarantis, 2012; Molden et al., 2012) on ego depletion. The resulting observation that these procedures did not lead to the detection of the originally reported effects underscores the relevance of independent replications. Furthermore, while there is no doubt that "failures to replicate previous findings are never conclusive" (Simmons et al., 2011, p. 1359), this standard should certainly be applied to the evaluation of "positive" findings as well. Along the lines of Schimmack (2012), the present results indicate that the effect sizes reported in the original studies on the role of blood glucose and oral glucose sensing in ego depletion are considerably inflated. These findings require models positing a major role for glucose in self-control to be fundamentally revised if not completely abandoned. Hence, providing evidence in support of the null hypothesis by means of a highly powerful research design might (in the absence of any significant *p*-value) make a significant contribution to the investigation of psychological phenomena.

Limitations

In contrast to most studies investigating the effect of ego depletion (Hagger et al., 2010), the same laboratory task was used as both depletion task and dependent measure in both of the experiments reported in the present study. Recently, Dewitte, Bruyneel, and Geyskens (2009) reported performances on a second self-control task to be impaired only after performing a different task. As a consequence, it remains possible that the present study failed to induce ego depletion and that the exhaustion of self-control resources can be moderated by sugar consumption or sensing only when dissimilar tasks are used. Wang and Dvorak (2010), however, reported a large effect of sugar drinks despite using identical tasks and, more crucially, limiting the study of ego depletion to paradigms using different tasks would contradict the basic assumptions of any resource model of self-control (Dewitte et al., 2009). Moreover, the related research in the domain of exercise physiology is entirely built on glucose administrations within the same task (i.e., running or cycling, Painelli et al., 2010). If carbohydrate mouth rinse improved persistence on cognitive and physical tasks in a similar way, one would expect to observe positive effects on cognitive performance when using identical self-control tasks as well.

Nonetheless, analyzing the role of glucose within the alternative cognitive control framework proposed by Dewitte et al. (2009) might provide valuable insight into mechanisms of conflict adaptation (Botvinick, Braver, Barch, Carter, & Cohen, 2001). As the observation of ego-depletion-like effects appears to depend on response conflict dissimilarity (i.e., the use of different self-control tasks), performance deficits on a second self-control task are more likely to be caused by the costs associated with task-set switching (Inzlicht & Schmeichel, 2012). Based on these ideas, future studies might investigate whether the facilitating effects of glucose can only unfold when participants have to adapt to novel response conflicts.

Conclusion

The effects of sugar consumption and sugar sensing on ego depletion have been systematically overestimated in previous studies. By scrutinizing the validity of these findings and presenting null results despite using powerful research designs, the present study demonstrates the absence of empirical reasons to believe that glucose plays more than a negligible role in self-control.

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