Impulsiveness, postprandial blood glucose and glucoregulation affect measures of behavioral flexibility

Leigh M. Riby[1], Derek Ong Lai Teik[2], Nurulnadia Binti Mohamad Azmie[3],Ee Lyn Ooi[3],Caroline Regina[3],Eugene Ki Wai Yeo[3], Jacqueline Massa[4], Luca Aquili[5,] *

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[1]Department of Psychology, Northumbria University, UK
[2]Department of Marketing, Sunway University, Bandar Sunway, Malaysia
[3]Department of Psychology, Sunway University, Bandar Sunway, Malaysia
[4]Department of Psychology, Kean University, Union, USA
[5]Department of Psychology, Sociology and Politics, Sheffield Hallam University, UK

*Corresponding author

E-mail: luca.aquili@shu.ac.uk
Tel: +44 (0) 114 225 6991; Fax: N/A

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Abbreviations

ACC= anterior cingulate cortex; BCST= Berg's Card sorting task; BF= behavioural flexibility; BIS-11= Barratt Impulsiveness Scale; BMI= body mass index; CPT= Continuous Performance Task; FBG= fasting blood glucose; GI= glycemic index; IGT= glucose tolerance test; PBG= postprandial blood glucose; RT= reaction time; VIF= variance inflation factor; WCST= Wisconsin Card Sorting Task

Abstract

Behavioral flexibility (BF) performance is influenced by both psychological and physiological factors. Recent evidence suggests that impulsivity and blood glucose can affect executive function, of which BF is a subdomain. Here, we hypothesized that impulsivity, fasting blood glucose (FBG), glucose changes (i.e. glucoregulation) from postprandial blood glucose (PBG) following the intake of a 15g glucose beverage could account for variability in BF performance. The Stroop Color-Word Test and the Wisconsin Card Sorting Test (WCST) were used as measures of BF, and the Barratt Impulsiveness Scale (BIS-11) to quantify participants' impulsivity. In Study 1, neither impulsivity nor FBG could predict performance on the Stroop or the WCST. In Study 2, we tested whether blood glucose levels following the intake of a sugary drink, and absolute changes in glucose levels following the intake of the glucose beverage could better predict BF. Results showed that impulsivity and the difference in blood glucose between time 1 (postprandial) and time 2, but not blood glucose levels at time 2 per se could account for variation in performance on the WCST but not on the Stroop task. More specifically, lower impulsivity scores on the BIS-11, and smaller differences in blood glucose levels from time 1 to time 2 predicted a decrease in the number of total and perseverative errors on the WCST. Our results show that measures of impulsivity and glucoregulation can be used to predict BF. Importantly our data extend the work on glucose and cognition to a clinically relevant domain of cognition.

1. Introduction

Behavioral flexibility (BF) refers to the ability to adaptively modify behaviors when changes in environmental demands occur, and is one of the core processes of executive function. BF is made up of several distinct processing mechanisms including the extinguishing of a response, inhibition, reversal learning, set-shifting and has been associated with creative ability [1, 2]. Two commonly used tests of BF include the Stroop Color-Word Test (measuring cognitive inhibition) [3-5] and the Wisconsin Card Sorting task (measuring set-shifting) [1, 6].

Impairments in tasks measuring BF have been reported in the clinical domain, for example in schizophrenics [1], OCD patients [7], stimulant addicts [8], frontal lobe patients [9], and in those suffering from Williams syndrome [10]. Importantly, many of these individuals have reportedly high levels of the personality trait impulsiveness [11]. One core feature of impulsive-related behavior is a deficiency in reversal learning and response inhibition, two specific subdomains of BF [12, 13].

Alongside neuropsychological tools, there have been several attempts to capture impulsivity using self-report scales. Arguably one of the most commonly adopted and cited scale of impulsiveness is the Barratt Impulsiveness Scale (BIS-11) [14]. Higher scores on the BIS-11 have been found to be predictive of poorer performance on tests of executive function/BF [15-18]. Furthermore, causal links have been found between impulsiveness, and biological markers (e.g. neurotransmitters; [19]), including the brain's primary fuel glucose.

For example, increasing the level of blood glucose by supplementation can reduce impulsive-related choice behavior [20-22]. Moreover, hypoglycemia (i.e. low blood glucose) has also been linked to impulsive related acts such as criminal behavior, sexual promiscuity, behaving

92 recklessly, and the likelihood of initiating and terminating alcohol and nicotine use [23-26].

93 Glucose supplementation has also been used to improve cognitive performance, primarily in the
94 areas of memory and attention [27-33], but more recently, also in tasks assessing executive
95 function and BF (indexed by performance on the Stroop) [34].While glucose supplementation can
96 improve cognitive performance, unusually low or high fasting blood glucose levels, as observed
97 in patients suffering from diabetes (type 1 and 2) can have detrimental effects on various aspects
98 related to executive function, memory, verbal reasoning, attention/vigilance and dual-tasking [35-
99 46].

100 More recently, postprandial glucose levels (plasma glucose concentrations two hours after eating
101 [[47]) have also been investigated as possible determinants of cognitive performance. There is
102 good reason for this, as fasting and postprandial blood glucose concentrations are mediated by
103 independent physiological mechanisms [48]. Thus far, some of these studies have found that a
104 low but sustained increase in blood glucose concentrations in the postprandial period is most
105 beneficial to enhance cognition, achieved by the provision of low GI (glycemic index) meals [49,
106 50]. Additionally, it is also clear that the ability to utilize glucose (i.e. glucoregulation) is a
107 contributing factor to cognitive functioning. Studies have shown that when examining changes in
108 blood glucose from the start of cognitive testing until the end, those individuals who displayed
109 decreased glucose levels performed cognitively better than individuals whose blood glucose
110 levels stayed at similar levels or even increased [51, 52]. Moreover, "poor" glucoregulators as
111 evidenced by blood glucose levels above 7.8 mmol/l following a 75-g oral glucose tolerance test
112 (IGT), demonstrated impaired cognitive performance in measures of executive function but not of
113 BF specifically [53-55].

114 Therefore, the objective of this research was to answer the following questions. First, given the

association between impulsiveness and executive function, we hypothesized that higher scores on the BIS-11 would predict impaired BF performance, as measured by the WCST, and the Stroop Color-Word Test. Second, given the relationship between impulsiveness and blood glucose, we hypothesized that fasting glucose levels could explain additional variance in BF. Previous findings have been contradictory with respect to an 'optimum' fasting blood glucose level as many of these have been tested in clinical populations (hence with particularly low or high fasting concentrations) and have assessed different cognitive functions. Third, while glucose supplementation has been shown to aid cognitive performance, this has most often been reported in contexts where fasting blood glucose levels are taken as a point of reference. However, in more realistic settings, it is likely that individuals perform a variety of cognitive-related tasks when their blood glucose levels are in a postprandial state. Thus, we took participants' postprandial state as a point of reference for glucose supplementation instead. Here, we predicted that glucose supplementation would be unlikely to confer a benefit to BF performance. Fourth, we hypothesized that individuals with lower changes in blood glucose from postprandial to blood glucose measured after glucose supplementation (i.e. "better" glucoregulators) would have superior BF performance.

To test this, we administered a more naturalistic dose of glucose (i.e. 15-g or equivalent to a glass of soda; see [56] for discussion of optimal dose and the inverted U shape curve) in healthy populations in their postprandial state. While the IGT has been primarily adopted as a screening tool to identify individuals with poor glucoregulation (i.e. diabetes), the 75-g glucose drink provided in the IGT does not represent a typical dosage that an individual would consume prior to completing a cognitive task.

2. Methods and materials

2.1. Participants

Sixty undergraduate volunteers (mean age 20.7 years, 38 females and 22 males, S.D. 1.5, study 1) and forty undergraduate volunteers (mean age 20.3 years, 27 females and 13 males, S.D. 1.4, study 2) were recruited in the study that was approved by the ethics committee of Sunway University Department of Psychology and complied with the Declaration of Helsinki. Sample size was determined using G*Power to establish a minimum power level of 80% based on linear multiple regression analyses containing three predictors (study 2) with an estimated large effect size (f^2) of 0.35. The selection of a smaller sample size in study 2 was in line with previous recommendations on sample size based on number of predictors in the model, size of the effect and statistical power [57, 58].Participants were excluded from the study based on a number of criteria. Approximately 10% of prospective participants who were contacted to volunteer in taking part in the study did not fulfil the eligibility requirements. Exclusion criteria included those individuals who declared they were consuming at least two cups of coffee a day on a regular basis, suffering from diabetes, and/or had other forms of glucose intolerance. After screening and prior to participation, each volunteer signed an informed consent form.

2.2. Cognitive measures

Cognitive testing was carried out using the Psychology Experiment Building Language (PEBL) test battery [59, 60]. Presentation of tasks occurred via laptop computers using VGA color monitors and to complete the two tasks, participants took approximately 15 minutes. The description of the cognitive tasks which follows is based on a previously published paper by our research group [61].

2.2.1. Stroop Color-Word test

This task is believed to measure selective attention, response inhibition and cognitive flexibility. Participants were required to determine the color that words appeared in (see Fig.1). In some trials, the words would correspond to actual color names. When this was the case, participants had to ignore the written color name and instead select the color of the word. Task measures were average reaction time (ms) for congruent, incongruent and neutral stimuli and total number of errors. There were a total of 87 trials. The first 24 were practice trials, while the remaining 63 were made up of congruent (n=20), incongruent (n=24) and neutral (n=19) trials. No other dependent measures were explored/tested.

2.2.2. Berg's card sorting test

This task is an adaptation of the Wisconsin Card Sorting Test (WCST) and measures complex executive functioning such as planning, cognitive flexibility, response inhibition, numerical skills and rules induction [62]. Participants were required to categorize cards based on the pattern appearing on them (see Fig.1). Each pile of cards had a different color, number and shape. A sample card would appear on the screen and participants were required to match this with one of the four piles of cards depending on a rule. Task measures included total number of errors and perseverative errors. There were a total of 128 trials with rule changing occurring 9 times (in an variable fashion across participants). No other dependent measures were explored/tested.

2.3. Psychological measures

2.3.1. Barratt Impulsiveness Scale (BIS-11)

The BIS-11 is a thirty-item self-report questionnaire designed to measure the personality trait of impulsivity [63]. Each item is rated on a 4-point Likert scale that ranges from 1 (rarely / never) to

4 (almost always / always). It is scored to yield a total score, three second-order factors (i.e. attentional, motor and nonplanning) and six first-order factors (i.e. attention, motor, self-control, cognitive complexity, perseverance and cognitive instability). Higher scores indicate higher impulsivity. The Cronbach's alpha for the current sample for total score was .79 and for each second-order subscales was .65 for attentional, .56 for motor and .67 for non-planning, similar to those previously reported [64] Test-retest reliability after a month interval for the total score and subscales scores has been found to be moderate (i.e. 0.61 to 0.83) [64].

2.4. Physiological measures

2.4.1. Blood glucose

Blood glucose readings were measured via capillary finger prick using Accu-Chek Performa diagnostic machines and test sticks (Roche Diagnostics, Germany). To minimize discomfort/pain, finger pricking was performed on the less painful lateral side of the fingertip. This is based on previous research investigating common practices amongst sufferers of diabetes when taking blood glucose measurements [65]. Blood glucose was collected once before cognitive tasks began (study 1). Participants were instructed to refrain from eating and drinking for three hours (i.e. fasting; for at least 180 minutes and no longer than 195 minutes) before their blood glucose was sampled (study 1). In study 2, blood glucose measurements were taken from participants having refrained from eating and drinking for two hours (i.e. postprandial; for at least 120 minutes and no longer than 135 minutes) instead of three hours as in study 1. A second blood glucose measurement was taken 15 minutes after having consumed a 15g glucose beverage.

2.5. Procedure

Testing was conducted in research-dedicated laboratories. Testing was carried out in the afternoon, between 2:00 p.m. and 4 p.m. Participants were first required to complete the BIS-11 questionnaire. Next, the participants' blood glucose levels (fasting) were measured by pricking a sanitized finger with the glucose meter lancet. After blood glucose levels were recorded, participants completed two computer based tests of behavioral flexibility, the Stroop Test (ST) and the Berg's Card sorting task (BCST) (study 1). The two tests were counterbalanced across participants. The whole experiment lasted approximately 25 to 30 minutes (study 1). Participants were given Cadbury chocolate bars at the end of testing as compensation. In study 2, following the first blood glucose measurement (postprandial), all participants received 15g of glucose dissolved in 200 mL of water flavored with 5 mL of no added-sugar lemon squash. The primary purpose of administering a glucose drink was to understand whether individual variability in the way glucose is processed modulated BF performance (i.e. glucoregulation). A secondary purpose was to capture variability in BF due to increased postprandial blood glucose. To avoid potential expectation bias of drinking a glucose beverage, we instructed participants that they may receive either a glucose drink or a placebo, even though this was not the case. To avoid this potential bias, in a prior small pilot study (i.e. n=20), we administered the same drink used during testing and found that when participants were asked whether they thought they had consumed a glucose drink or a placebo, the response rate for the glucose drink was at chance factor (i.e. 54%). Fifteen minutes after the glucose drink, a second blood glucose measurement was taken and cognitive testing began. The whole experiment (study 2) lasted approximately 45 minutes (see Fig.2).

2.6. Statistical analyses

Statistical analyses were performed using SPSS Statistics version 22 (IBM, Armonk, NY, USA). A *P* value less than .05 was deemed significant. Data are shown as means and SD ±. Several hierarchical multiple regression analyses were performed to examine the contribution of psychological and physiological predictors (i.e. impulsivity and FBG in study 1 and impulsivity, blood glucose 15 minutes following glucose intake [time 2] and changes from PBG [time 1] to blood glucose following the intake of a glucose drink [time 2] in study 2) to outcomes of BF (i.e. Berg and Stroop task performance). Examinations of collinearity and independence of errors were used to rule out potential confounding variables. An independent-sample t test was conducted to compare fasting and postprandial blood glucose between study 1 and 2.

3. Results

3.1. Study 1

In order to determine the contribution of impulsiveness (as measured by the BIS 11 scale), and fasting blood glucose levels to measures of behavioral flexibility (i.e. Berg and Stroop), we used hierarchical multiple regression analyses. Mean and standard deviation scores for both predictors and outcome variables are presented in **Table 1**. A preliminary examination of collinearity statistics (i.e. variance inflation factor [VIF] and tolerance) demonstrated that multicollinearity was not an issue (i.e. VIF= 1.028; Tolerance= 0.98). The data also met the assumption of independent errors (i.e. Durbin-Watson= 1.52-2.27).

In the first step of the analysis, we added the measure of BIS-11 total score (i.e. impulsiveness) as predictor. In the second step of the analysis, we added fasting blood glucose levels (eating and drinking avoided for 3 hours prior to blood glucose testing). The four dependent variables consisted of the total number of errors in the Pebl's Berg Card sorting task, perseverative errors, reaction time (RT) and total errors on the Pebl's Stroop task. The summary of the hierarchical multiple regression analyses are presented in **Table 2.** Neither BIS-11 total score nor fasting blood glucose levels contributed significantly to the regression model for any of the four criterion variables. It has been suggested [66] that the BIS-11 total score may be an imperfect measure of impulsivity, thus we ran additional analyses exchanging the BIS-11 total score with three subdomains of impulsivity, namely attention, motor and non-planning (which individually contribute to the BIS-11 total score). Results of these analyses were also non-significant.

To sum up, and contrary to our predictions, neither impulsivity nor fasting blood glucose levels could account for variability in behavioral flexibility (BF) performance.

3.2. Study 2

An independent sample t-test was conducted to assess whether blood glucose levels were different between participants in experiment 1 and those in experiment 2 (3 hours fasting versus 2 hours postprandial). This analysis was carried out to ensure that the instructions to refrain from eating or drinking for either two or three hours did in fact result in differential blood glucose readings between the studies. Because sample sizes were unequal between the two experiments (i.e. n=60 vs n= 40), we randomly selected a sample of 40 participants (out of the total 60) (using SPSS's Select Cases function) in experiment 1 and compared these with the 40 participants in experiment 2. Results showed that participants in experiment 2 had significantly higher blood glucose levels (6.23 ± 1.36) than participants in experiment 1 (5.58 ± 1.02) t (72.47) = 2.31, p =0.024, d =0.61.

As in experiment 1, hierarchical multiple regression analyses were used to determine the contribution of impulsiveness (as measured by the BIS 11 scale), blood glucose levels after a glucose drink (time 2) and changes in blood glucose from postprandial blood glucose (time 1) to time 2 to measures of behavioral flexibility. Mean and standard deviation scores for both predictors and outcome variables are presented in **Table 1**. A preliminary examination of collinearity statistics (i.e. variance inflation factor [VIF] and tolerance) demonstrated that multicollinearity was not an issue (i.e. VIF=1.021-1.064; Tolerance= 0.94-0.98). The data also met the assumption of independent errors (i.e. Durbin-Watson= 1.49-1.89).

In the first step of the analysis, we added the measure of BIS-11 total score (i.e. impulsiveness) as predictor. In the second step of the analysis, we added blood glucose levels after a glucose drink. In the third step of the analysis, we added changes in blood glucose from postprandial (time 1) to time 2 (following the sugary drink). The four dependent variables are the same as in experiment

1. The summary of the hierarchical multiple regression results is presented in **Table 3** and **Figure 3.** BIS-11 total score, blood glucose levels after a glucose drink, and changes in blood glucose from time 1 to time 2 did not contribute significantly to the regression model in two of the four criterion variables (i.e. reaction time (RT) and total errors on the Pebl's Stroop task).

However, BIS-11 total score entered at step 1 explained 10.6% of the variance in total number of errors in the Pebl's Berg Card sorting task, $F(1,38) = 4.51$, $p=0.040$. Introducing blood glucose levels after a glucose drink at step 2 did not produce a significant change in R^2 as it only explained an additional 8.3% of variation in Berg total errors, $F(1, 37) = 3.78$, $p=0.059$. Finally, adding changes in blood glucose from time 1 to time 2 produced a significant change in R^2, as it explained an additional 19.2% of variation, $F(1,36) =11.19$, $p=0.002$. Together, the three independent variables accounted for 38.1% of variance in Berg total errors, $F(3, 36) =7.40$, $p<0.001$.

We then looked at perseverative errors in the Pebl's Berg Card sorting task, as this represents a separate measure of behavioral flexibility impairment, namely the repetition of particular (erroneous) response at least twice consecutively. BIS-11 total score entered at step 1 explained 11.7% of the variance, $F(1,38) = 5.04$, $p=0.031$. Introducing blood glucose levels after a glucose drink at step 2 did not produce a significant change in R^2 as it only explained an additional 1.8% of variation in Berg perseverative errors, $F(1, 37) = 0.76.$, $p=0.387$. Finally, adding changes in blood glucose from time 1 to time 2 produced a significant change in R^2, as it explained an additional 25.3% of variation, $F(1,36) =14.89$, $p<0.001$. Together, the three independent variables accounted for 38.8% of variance in Berg perseverative errors, $F(3, 36) =7.61$, $p<0.001$.

Therefore, the lower the blood glucose increases from time 1 to time 2, the better the BF performance. Moreover, higher postprandial blood glucose levels (time 1) were predictive of

lower changes in blood glucose from time 1 to time 2. In fact, participants in the top quartile of postprandial blood glucose concentrations (7.85 mmol/l) had an average increase in blood glucose at time 2 of 1 mmol/l, whereas those in the bottom quartile (4.51 mmol/l) an average increase of 2.3 mmol/l. These differential responses were in turn related to fewer total and perseverative errors on the WCST (see Fig.4). A simple linear regression analysis confirmed that blood glucose levels between the postprandial measurement (time 1) and the difference between time 1 and time 2 were negatively correlated, r= -.533, n=40, p= < .001. This finding is surprising given that, for example, fasting blood glucose levels have been reported to have a positive correlation with postprandial measurements [67].

4. Discussion

The current investigation had four principal objectives: (1) to further our understanding of the relationship between impulsiveness and behavioral flexibility (BF) (study 1 and 2); (2) to explore whether fasting blood glucose levels can be used to predict BF (study 1); (3) to examine whether glucose levels measured following glucose supplementation from a postprandial state can explain BF performance (time 2); (4) to investigate whether blood glucose changes from a postprandial state (time 1) to blood glucose measured following the intake of a sugary drink (time 2) can further be used to predict BF (study 2). To answer these questions, we devised two separate experiments. In study 1, we found that neither impulsiveness nor fasting blood glucose levels could account for variation in performance of the BF tasks (WCST and the Stroop task). In study 2, we found that higher levels of impulsiveness could predict increased number of errors on the WCST but not on the Stroop task. Moreover, we found that blood glucose levels measured 15 minutes after the sugary drink intake did not explain significant improvements on the WCST nor on the Stroop. Importantly, however, lower increases in blood glucose from postprandial blood glucose to 15 minutes after the glucose drink were related to a reduction in the number of errors on the WCST but not on the Stroop.

At first glance, the findings that impulsiveness could predict BF in experiment 2 but not in 1 seem puzzling, particularly given that mean scores on the BIS-11 were almost identical in both studies. However, because participants in study 1 and 2 differed on the basis of their fasting versus postprandial blood glucose profile, and on whether they received additional glucose prior to cognitive testing, these data should be interpreted taking these methodological differences into account. A performance comparison on the WCST between study 1 and study 2 participants (30.7 vs 26 errors), does in fact suggest that that a combination of postprandial blood glucose levels

and taking additional glucose can alter negatively performance. Therefore, it is plausible that the BIS-11 scale is capturing variability in BF when cognitive performance declines. Previous research had demonstrated a relationship between the BIS-11 and measures of BF [15-17]. However, in the above studies no measures of blood glucose concentrations were taken, and presumably most participants would have performed tasks of BF in a non-fasting and/or non-postprandial plus glucose intake state. Therefore, our data indicate that high impulsiveness is predictive of impaired BF performance in individuals who perform the task during their postprandial blood glucose levels plus glucose supplementation (more naturalistic state) but not in those in a fasting state.

We hypothesized that fasting blood glucose (study 1) could predict BF performance, however, this was not the case. Previous investigations which have reported a link between executive function and fasting blood glucose have been based on diabetic patients either hypoglycemic at fasting (i.e. <3.0 mmol/l) or hyperglycemic (i.e. >7.00 mmol/l). Blood glucose values at fasting below or above these thresholds negatively impact cognition. Some studies have shown that fasting blood glucose levels in a healthy, younger population below 4.1 mmol-l were detrimental to executive function (although not BF specifically) [68]. It would thus appear that fasting levels in the 5.5 mmol/l ± 0.9 range, as in the current study, bring about comparable BF performance across participants. This is in agreement with a large study in an elderly cohort whereby no association was found between fasting glucose levels in the 5.14 mmol ± 0.78 and executive function [69]. In contrast, our findings disagree with a recent study in which older, healthy participants with higher fasting blood glucose levels in the 4.91 mmol/l ± 0.57, showed impaired executive function performance [70]. However, it should be stressed that there are inherent difficulties in comparing the findings from studies in which young and older adults were

employed due to different gluco-regulatory profiles and particularly because we know that characteristics such as age, BMI (body mass index) and a history of prior disease can negatively influence cognitive performance [71].

In study 2, we also found that blood glucose measured following the intake of a sugary drink (time 2) from a postprandial state did not account for variability in BF performance, as per our hypothesis. This finding suggests that once a certain blood glucose threshold has been reached (in our study 7.6 mmol/l ±1.2), BF performance is unaffected. These results are not particularly surprising given that previous investigations have shown that cognitive improvements in memory, attention and executive function are only found when participants blood glucose levels raise to approximately 8.9 to 10 mmol/l, and when contrasted to placebo groups with fasting blood glucose levels of 4.2 to 5.3 mmol/l [72, 73]. Because all participants in our study 2 did take the glucose drink, and because their baseline postprandial blood glucose (i.e. pre-glucose supplementation) was significantly higher, blood glucose variations across participants were within a much narrower window (i.e. 7.6 mmol/l ± 1.2) than in previous studies to allow for cognitive performance differences to be picked up.

The most noteworthy finding from this study is that the lower the change (i.e. from postprandial blood glucose) in blood glucose levels following the consumption of a 15-g glucose drink, the better the performance on the WCST. These data are largely in agreement with previous investigations on other cognitive functions [51-55] and extend to the domain of behavioral flexibility. Moreover, however, our study uniquely shows the importance of glucoregulation on cognitive performance even when a small dose of glucose has been administered to individuals in their postprandial and not fasting state. Those adopting to track blood glucose and obtain an estimate of glucose regulation throughout the testing session tend to administer 25g or 50g

depending on whether younger or older adults are examined, respectively (see [56] for meta-analysis; [74] for review). Previous studies have also adopted to administer the glucose tolerance test (i.e. overnight fasting followed by the ingestion of a 75-g glucose drink) in a separate session as a measure of glucose regulation. Whilst this method can be used as a diagnostic tool for type 2 diabetes, we aimed to use a smaller glucose dose as a more naturalistic indicator (15-g or equivalent to a glass of soda) of an individual's intake prior to performing a cognitive related task in an everyday setting.

Further analyses of our data also showed that higher postprandial blood glucose levels were predictive of smaller changes in blood glucose levels following glucose supplementation. This is in contrast with a previous study in which high fasting blood glucose levels were predictive of high postprandial blood glucose [67]. Because we measured glucoregulation from a postprandial state and not a fasting one, a direct comparison with the above study cannot be made. Importantly, however, our data suggest that glucoregulation is a mechanism that is at least partially modulated by postprandial glucose levels, rather than being independent from it. Future studies would need to identify participants with similar postprandial profiles (i.e. within a 1mmol/l range as opposed to over 2mmol/l in this study) to find out whether glucoregulation is independent from postprandial glucose levels in affecting BF performance.

Finally, in both experiment 1 and 2, impulsiveness, fasting blood glucose levels, glucose levels at time 2 and changes in blood glucose following the intake of a 15-g glucose drink did not account for variability in Stroop performance. Nevertheless, our findings may be explained by the observation that although there is great overlap between the neuronal substrates that determine performance on the WCST and Stroop, there is also some evidence to suggest that performance on the Stroop task relies more heavily on the anterior cingulate cortex (ACC) [75-77], whereas

performance on the WCST on the dorsolateral and ventromedial prefrontal cortex [78-80]. Cognitively there is also good reason to suspect the task tap different processing mechanisms. For instance, Goshiki & Miyahara [81] in their examination of the tasks within a working memory framework argue that the WCST recruits both the phonological loop and central executive components; whereas the Stroop the central executive only.

Future studies would need to address some limitations of the current investigation. First, as participants verbally reported the time from last consumption of a meal, it is possible that the fasting and postprandial definitions of three and two hours without eating or drinking may have not been strictly adhered to. However, the blood glucose values for both the fasting group (study 1) and postprandial group (study 2), are largely in line with previously reported studies [47, 82]. Second, as meal composition intake prior to measuring fasting (study 1) and postprandial (study 2) glucose levels was not monitored, there may have been effects of eating food with different protein, carbohydrate, fat and micronutrients on BF performance unrelated to absolute blood glucose concentrations per se, but for example due to variation in glucose metabolism, glucagon to insulin ratio, hormonal and mood effects [83].

In conclusion, our findings provide support for a larger body of knowledge which links impulsiveness and glucose regulation to executive function and extend to the domain of BF specifically. Additionally, the effect of glucose regulation on BF was mediated using more naturalistic glucose dosages than in previous investigations, and was partially affected by participants' postprandial blood glucose profile.

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