

**The impact of glucose on Bayesian v. heuristic-based decision making**

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## Abstract

We examine the impact of glucose in a choice task that can distinguish Bayesian from lower-level reinforcement heuristic choice. Drawing from a dual systems framework, we hypothesize that glucose administration will increase reaction times and improve Bayesian accuracy because it should shift decision making towards the more deliberate system 2 and away from the more automatic system 1 decision process. We study 113 subjects randomly assigned to either a glucose or placebo drink condition, who make choices over several incentivized easy and difficult choices of the Bayesian task. Our results indicate a significant and robust glucose effect on reaction times. Glucose administration has a main effect of increasing reaction time, as predicted, but glucose also improves the marginal decrease in reaction times across trials. Regarding Bayesian accuracy, we analyze subject choice possibilities as states satisfying the properties of a regular discrete Markov chain (choices may be Bayesian, Reinforcement, or also Naïve). We calculate steady-state Markov probabilities and show that glucose increases the likelihood of making a Bayesian choice over a heuristic-based choice by up to 9%. These results suggest a beneficial impact of glucose on deliberative decision making.

**Keywords:** Bayesian Choice, Glucose, Learning, Experiments

Glucose is the primary fuel source for the brain, including both the lower limbic regions and the outer cortex. Consequently, most, if not all, cognitive functioning is dependent upon glucose. Because glucose is such a key element in the human thought process, researchers have shown interest in examining the role that glucose plays in many facets of cognitive functions and behavior, including decision making. In this paper, we test the hypothesis that glucose administered subjects will favor choices requiring deliberate thought over heuristic-based. More specifically, we use a modification of the decision task in Charness and Levin (2005), where certain trials create a divergence between the choice a Bayesian subject would make versus the choice one would make if following a simple reinforcement heuristic rule.

### **Glucose and Cognition**

Blood glucose is an important determinant of cognitive function (Donohoe & Benton, 1999). Because cognitive functioning is an encompassing term, research findings should be considered specific to each particular type of cognitive functioning and its consequential processing. For example, cognitive impairment of working memory may not mean impairment for decisions dependent upon long-term memory retrieval. It is also important to make the distinction between how glucose level interacts with cognitively complex or simple tasks. Several studies have shown that glucose enriched participants performed better on more cognitively complex tasks, but their performance did not differ on cognitively simple tasks (Kennedy & Scholey, 2000; Scholey et al, 2001).

Glucose seems to be a potent player in at least some types of memory performance. One of the most influential types of memory that has been studied is verbal memory. A series of studies seem to show a consistent pattern of glucose enriched participants outperforming glucose

deprived participants in verbal memory tasks (Messier et al, 1998; Sünram-Lea et al 2001; Sünram-Lea et al, 2002). There is also evidence that glucose enriched participants perform better on spatial memory (Sünram-Lea et al, 2001) and spatial working memory tasks. Meikle et al (2004) investigated glucose effects, cognitive performance, and the role that age plays in mediating general or memory-dependent measures of cognition. They found that glucose effects seemed to be exclusive to memory-dependent measures and this effect seemed to be exacerbated in middle-aged participants as compared to younger subjects. Such research highlights the importance of selection tasks for behavioral research on glucose effects that do not involve a significant memory component to performance, since doing so would present a confound in the data.

Other research, however, clearly shows that glucose effects are not restricted to memory-dependent measures of cognition. Research has shown that glucose deprivation can influence the more thoughtful processes as well.<sup>1</sup> For example, choice that involves impulse control, which is an effortful cognitive endeavor, has been found to deplete blood glucose levels (Gailliot & Baumeister, 2007) and other research has reported that supplemental glucose eliminates self-control impairments resulting from depleted glucose reserves (Gailliot & Baumeister). These results regarding glucose and self-control may be largely explained, however, by differences in one's beliefs about willpower and self-control, as shown in Job et al (2013). Other research has shown that glucose administration reduces the use of stereotypes (Gailliot et al, 2009)<sup>2</sup> and

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<sup>1</sup> Danzier et al, (2011) results are consistent with the possibility that blood glucose levels may impact important real world environments such as parole decisions.

<sup>2</sup> Bodenhausen (1990) show that decision-making at one's more preferred time of day also reduces the use of stereo-types. Thus, there is a consistency in the behavioral effects of some factors believed to similarly affect

improves patience for future rewards (Wang & Dvorak, 2010), which is consistent with a preferential impact of glucose on prefrontal brain regions that show increased activation when more delayed rewards are chosen (McClure et al, 2004). The result of glucose administration on preference for delayed payments may not be without controversy, however. For example, Kuhn et al, (2013) find that both glucose and a placebo drink promote similar increases in delayed payments preference.

### **Glucose Implications for Decision Making**

A more specific question for our investigation is how glucose may influence decision making. Existing research (e.g., impulse control, time discounting, use of heuristics) seems to indicate that glucose may preferentially impact executive function regions of the brain that are more active with deliberate thought. In the context of a dual-systems framework of brain function (e.g., Schneider & Shiffrin, 1977; Camerer et al, 2005; Kahneman, 2011), this would imply that additional glucose shifts the relative weight of decision making away from the more automatic System 1 in favor of the more deliberative System 2.<sup>3</sup> Interestingly, not all studies finding a glucose effect involve actual glucose consumption. To some extent, the brain may react to the mere presence of glucose, which highlights the complexity of glucose effects.<sup>4</sup>

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cognitive resources (i.e., glucose depletion or sleepiness would both be considered a depletion of cognitive resources).

<sup>3</sup> Neural evidence indicates that system 1 and system 2 thinking activate different parts of the brain (Goel et al 2000).

<sup>4</sup> Molden et al (2012) show that rinsing one's mouth with a sugared beverage improves self-control, a result previously linked to consumption of the glucose (Gaillot et al, 2007). Such a result implies the brain may anticipate the forthcoming delivery of glucose, because certain behavioral effects from gargling without ingesting are shown to be similar between a glucose and non-glucose drink (Sanders et al, 2012). Indeed, there is activation in the brain when one smells, tastes, and consumes food or drink (Kringelback, 2004), and research has shown that glucose in the mouth triggers sensors that activate reward and motivation areas of the brain (Carter et al, 2004; Gant, et al, 2010). This complicates the interpretation of glucose effects since some effects may be enjoyed without the fuel increase to the brain (see Kuhn et al (2013) for description of this literature). If glucose activates

Masicampo and Baumeister (2008) examined glucose effects in an attraction task, which presents the participants with two alternatives that are approximately equal in desirability. A third unattractive “decoy” alternative is then added. Importantly, the decoy alternative is very similar to one of the two “real” alternatives. Prior studies show that participants will change their preference to that of the alternative most similar to the decoy. Masicampo and Baumeister found that the glucose-deprived participants relied more on the decoy alternative when making decisions compared to the glucose enriched participants. These results are consistent with the hypothesis that glucose limits the influence of irrelevant auxiliary factors in the decision environment.

Another study, to which ours is closely related in spirit, focused on how glucose affected decision making in a probability judgments task. In McMahon and Scheel (2010), participants had to choose which of two events were likely to occur in each of 200 decision rounds, and one event was set to occur more frequently than the other (e.g., 70% of the time). This environment typically gives rise to phenomenon of probability matching, whereby a subject selects each alternative with the same frequency as its occurrence, even though one should select the more likely alternative in every round to maximize expected payoffs. McMahon and Scheel found that glucose enriched subjects were actually *more* likely to probability match, while glucose deprived participants used the probabilistically more optimal strategy more often. They explain this paradoxical result by presenting some evidence that glucose enriched subjects engaged in

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the reward centers focused on the reward of glucose (as opposed to our payoff rewards) then our results would be a conservative estimate of the effects of glucose as fuel for cognitive thought. This is because any increase in anticipation of a glucose reward would be considered a more automatic System 1 process that works opposite our hypothesis regarding glucose and effortful thinking.

normative rule generation, which requires deliberate thought, but we must also note that subjects were not incentivized in the task to receive a higher payoff for increased accuracy.

### **Summary and predictions**

One indicator of deliberate thought processes at work in a decision task is reaction time (Kahneman, 2011). This leads to:

*HYPOTHESIS 1:* Glucose subjects will have longer reaction times.

Regarding the quality of choices (i.e., choices consistent with more likely outcomes), the existing literature leads to a clear hypothesis regarding glucose effects. Glucose supplementation should facilitate system 2 processing and therefore increase the incidence of Bayesian choice, in particular when choices are more difficult. As we discuss later, Bayesian errors in the Easy trials of our task imply decisions that are also inconsistent with the Reinforcement heuristic, and so they likely indicate a naïve subject who does not fully understand the stimulus. Thus, we have:

*HYPOTHESIS 2:* Glucose subjects will be more likely to make Bayesian choices than no-glucose subjects (alternatively, Bayesian errors will be significantly lower in the glucose condition).

## **Method**

### **Participants**

A total of 113 subjects (56 female) took part in the experiment. Of these, 27 females were in the glucose condition (29 were no-glucose) and 29 males were in the glucose condition (28 were no-glucose). Subjects were recruited from a standard Psychology department subject

pool, which consists of Psychology majors and non-majors. The experiments were approved by our institution's IRB for the use of human subjects.

## **Materials**

**Glucose manipulation.** Prior to the experimental session a research assistant prepared lemonade drinks for the study. We used 12 oz. Minute Maid regular and diet Lemonade drinks to manipulate glucose levels. The regular Lemonade contained 40 g of sugar and the Light Minute Maid Lemonade contained 0 g of sugar. Each drink was masked so that no parts of the can were visible. The can was coded with subject number and condition (glucose or placebo), which was recorded in a password-protected spreadsheet for later identification. Therefore, the condition was double-blind—neither the subject nor the experimenter were aware of the subject's assigned condition during the experiment session.

**Bayes Switching Task.** The task involved 40 timed rounds or trials. In each trial, the subject was presented the stimulus in stage 1 (Fig. 1). There is a 50% chance of being in the Up or Down row, determined by a hidden draw prior to stage 1 of the trial. The computer selects a column in stage 1, a ball is then drawn from the resultant cell, and the subject is informed of both the column selected and the color of the ball drawn. The ball is replaced, and the subject must then choose which column to select in stage 2 of the trial, knowing the row from stage 1 remains the same for both stages of the trial. The subject had 6 seconds to make a stage 2 column choice (deemed adequate in pilot experiments), and subjects were informed that a black ball drawn in stage 2 would earn them \$10 (a white ball would earn them nothing). The stage 2 outcome was



shown prior to the start of the next trial. Subjects were informed that, after all trials were completed, one randomly selected trial would count for actual payoff.

The task was programmed to automate half the trials to select the LEFT column in stage 1, and half would select the RIGHT column (randomized across the 40 trials). Note that stage 1 draws from the RIGHT constitute what we call Easy trials or tasks, because Bayesian and Reinforcement choices are aligned. For example, if a black ball is drawn from the RIGHT column in stage 1, a Reinforcement subject would choose RIGHT again in stage 2 because RIGHT produced a winning ball in stage 1. A Bayesian subject would also choose RIGHT in column 2 because a stage 1 black ball from RIGHT reveals to the subject that this trial is in the UP row. Therefore choosing RIGHT in stage 2 is Bayesian because it maximizes the probability that a black ball will be drawn in stage 2. The more difficult trials are those where the stage 1 draw is from the LEFT, in which case Bayesian and Reinforcement choices will diverge. A black ball drawn from stage 1 LEFT would lead a Bayesian subject to switch and choose RIGHT in stage 2, because the UP row is more likely and choosing stage 2 RIGHT would again maximize the chance of a black ball. However, a Reinforcement subject would stick with LEFT in stage 2 if black ball is drawn from LEFT in stage 1.

The task was programmed in E-Prime® software, which generates accurate response time data for each trial. After on-screen instructions (see Supplementary Materials), four practice trials first familiarized the subjects with the stimulus-response process explained in the instructions.

## **Procedure**

When participants signed up they were told to fast for at least three hours before the session. As such, no signups within 24 hours of the session were allowed, and individuals with glucose sensitivity were asked not to sign up for the study. The evening before each session, participants were emailed and reminded to fast for at least three hours before the experiment session was set to begin. Study sessions took place during the morning hours to help participant's comply with the fasting requirement. Thus, participants should all have arrived in a glucose-deprived state.

Participants were run in a computer lab in groups of up to 9 subjects. After obtaining informed consent, participants were asked to drink their lemonade can as quickly as possible. After finishing the lemonade drink, several unrelated filler tasks were presented for the next 15 minutes. This time allowed the glucose to adequately absorb into the bloodstream.<sup>5</sup> Directly after completion of the filler tasks participants were instructed to begin the computerized task. The on-screen instructions clearly described how the task was incentivized with the potential to earn \$10 cash if a black ball was drawn in stage 2 from a randomly selected decision round. After all subjects were finished with the task, subjects were given their payoffs individually and in private.

## **Results**

### **Unconditional Nonparametric Analysis**

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<sup>5</sup> Wang and Dvorak (2010) show that a 10-minute wait time is sufficient for significantly increased blood glucose levels after consumption of a sugared soft drink (compared to placebo diet soft drink), and Kennedy and Scholey (2000) show a sustained significant increase in blood glucose at 24min and 45min following consumption of a 25 g glucose drink (our treatment drink contained 40 g of sugar).

Reaction times are first analyzed using Mann-Whitney means tests. The data are initially pooled across trials and subjects. Results of these nonparametric tests indicate that reaction times are significantly higher in the glucose condition ( $p < .01$ ), and the results hold for comparisons split by gender and task difficulty ( $p < .01$  both Easy and Hard task comparisons of the glucose effect for females, and  $p < .10$  for both Easy and Hard task comparisons for males). If one averages reaction times across all trials for a given subject, the Mann-Whitney tests only indicate a marginally significant decrease in *average* reaction time in the glucose condition for females in the Easy trials ( $n=57$ ,  $p=.06$ : all others  $p > .10$ ). This approach fails to utilize all the data, which we address in the next section. Nevertheless, we take these results as an initial indication of glucose effects on reaction times and the possibility that the effect may vary across trials and possibly gender.

Because Bayesian accuracy (or Bayesian errors) is a binary outcome variable, we conduct initial nonparametric analysis on Bayesian accuracy with two-sample proportions tests. We code a response as a “Reinforcement Choice” if it is consistent with the reinforcement heuristic, and we code as a “Bayesian Choice” if the choice is consistent with Bayes rule. Only the hard trials (i.e., stage 1 LEFT trials) can discriminate Bayesian and Reinforcement choices, and so we test the null hypothesis that the proportion of Bayesian choices equals the proportion of Reinforcement choices in the subset of Hard trials. In separate tests with the glucose and no-glucose data, we reject the null hypothesis in favor of the alternative that Bayesian choices are more likely than Reinforcement choices ( $p < .01$  in both cases).

To examine glucose effects on Bayesian accuracy, we first conduct binomial tests of the null hypothesis that the proportion of Bayesian errors of the glucose subjects is equal to the

proportion of Bayesian errors of the no-glucose subjects. We reject the null hypothesis in favor of the alternative that glucose subjects make fewer Bayesian errors on Hard trials (44% versus 47% Bayesian errors,  $p < .03$  for the 1-sided test), but fail to reject the null for the Easy trials (30% versus 31% Bayesian errors,  $P > .10$ ).<sup>6</sup> Thus, the unconditional analysis shows some evidence indicating that glucose improves Bayesian accuracy on Hard trials. Alternatively, we can pool all trials for a given subject and use each subject's overall Bayesian accuracy as the unit of observation and conduct tests across samples of glucose and no-glucose subjects. Such Mann-Whitney two sample tests indicate no significant impact of glucose on Bayesian accuracy ( $p > .10$ ). However, two items are noteworthy. First, much like pooling reaction times across trials, this approach wastes information on trial-specific choice. Secondly, as previously noted, Bayesian choice cannot be distinguished from Reinforcement choices on the Easy trials, and so we need a more proper analysis that takes this into account, which we do in the next section.

### **Multi-variate Panel Data Analysis**

Our data represent a panel of 4520 observations (113 subjects x 40 trials), roughly half of which (56 subjects) are in the glucose condition. A small number of observations were lost due to subjects failing to respond prior to the end of the 6-second trial response window, resulting in a final sample of 4507 trial-level choices. Data are pooled across gender due to weak evidence of any robust gender effects in the multivariate analysis (see supplemental material for reaction

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<sup>6</sup> This glucose effect on Hard trials is more significant for male subjects and is statistically insignificant for female subjects.

time analysis with gender variables).<sup>7</sup> In focusing on examining glucose effects, we first analyze reaction time data using a random effects GLS estimation (indexed by subject and trial):

$$(1) \text{ Reaction Time} = \alpha + \beta_1 \text{ Trial} + \beta_2 \text{ Hard Trial} + \beta_3 \text{ Glucose} + \beta_4 (\text{Glucose} * \text{Trial}) + \text{error}$$

The results are shown in Table 1, column 1. The significant negative coefficient on *Trial* indicates that reaction times decrease across trials, ceteris paribus, which is evidence of a type of learning. Reaction times are also estimated to be significantly longer for *Hard Choice Trials*. This is consistent with the hypothesis that harder choices will engage system 2 deliberate thought. Consistent with Hypothesis 1, glucose administration has the main effect of increasing reaction times. Though not part of our initial hypotheses, the results in Table 1 also reveal a significant interaction effect between *Glucose* and *Trial #*. Specifically, glucose administered subjects experience a significantly steeper declining reaction time trend across trials than the no-glucose subjects. Columns 2 and 3 in Table 1 show results from separate estimations for Easy and Hard trials, and we find the reaction time result is robust across trial difficulty.

This reaction time result is shown visually in Fig. 2. Thus, our results are consistent with Hypothesis 2—glucose will increase reaction times consistent with increased deliberate thought—but we estimate an additional glucose learning effect as proxied by reaction times. While our interpretation of these faster response times is that glucose improves efficiency of cognitive processing, an alternative interpretation is that faster response times over time indicate

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<sup>7</sup> There is evidence that glucose metabolism may differ in task-specific brain regions by gender (Haier and Benbow, 1995). Summary data show some gender differences in Bayesian accuracy, but they are not robust and the marginal differences identified occur only in Easy trials when estimating the following random effects probit model  $\text{Bayes Error} = \alpha + \beta_1 \text{ Trial\#} + \beta_2 \text{ Hard Trial} + \beta_3 \text{ Glucose} + \beta_4 (\text{Glucose} * \text{Trial \#}) + \text{error}$  Because Bayesian errors on Easy trials can only imply subject misunderstanding of the stimulus, we feel that such an analysis would be a misspecification of the model (nevertheless, results available on request).

fatigue and a movement towards automatic system 1 processing. However, results from analysis below are not consistent with this alternative interpretation.<sup>8</sup>

### **Bayesian Accuracy**

As noted before, a concern with regards to Bayesian accuracy in this task is the fact that subject choices may also fail to be either Bayesian or Reinforcement in the Easy trials. We create a measure of apparent comprehension of the task by counting the total number of instances across the 20 *Easy* trial choices in which the subject made a Bayesian/Reinforcement choice. Call this individual-specific variable *Task IQ*, which ranges from 0 to 20 by definition. The mean *Task IQ* of our subjects is 13.8 (median=12), and so this documents that Bayesian errors even on Easy trials are not uncommon among our subjects.<sup>9</sup> Because errors exist on Easy trials, subject choices can be divided into three types: Naïve (Bayesian/Reinforcement inconsistent on Easy trials), Reinforcement (follows this heuristic on Hard trials), or Bayesian (follows Bayes rule on Hard trials). Note that each choice “state”—Naïve, Reinforcement, Bayes—becomes more likely the more deliberate thought is engaged by the subject.

### **Markov Steady State Probabilities**

We model the subject’s choice probabilities across trials as a discrete regular Markov chain. That is, we use the transition probabilities in going from one state to another to calculate the steady state probability distribution of choice states. This process assumes the probability of

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<sup>8</sup> Specifically, this is because our analysis will show that glucose improves Bayesian accuracy, and thus we have data indicating a pure effect of increased reaction times and increased accuracy due to glucose. This is also consistent with the initial nonparametric analysis we conducted which showed significantly increased reaction times and significantly improved Bayesian accuracy for glucose subjects. If the extra improvement in reaction times across trials due to glucose were due to fatigue and a switch to more system 1 automatic choice, we would not expect to see increased Bayesian accuracy.

<sup>9</sup> A binomial test indicates a 4% probability that a subject merely making random choices would get 14 of 20 trials Bayesian correct, so the average subject in our experiments does better than this 50% random choice accuracy benchmark.

the next state in the next trial is only a function of the current state. This simplifying assumption allows for straightforward calculation of steady state Markov probabilities. For this analysis, only trials where a subject's choice can be uniquely scored into one of these 3 choice states are used (i.e., *Easy Choice* where choice is both Bayesian and Reinforcement consistent are discarded). Restricting the analysis to subjects with higher than average *Task IQ* scores implies the steady state probabilities will be concentrated in the Reinforcement and Bayes categories. Our focus, of course, is to examine whether the steady state probabilities from the glucose subjects are higher than those of the no-glucose subjects for the Bayes choice state (relative to Reinforcement state, in particular).<sup>10</sup>

Let  $p_{ij}$  represent the transition probability of going from state  $i$  to state  $j$ . If we use subscript notation  $N, R, B$ , to denote the respective states Naïve, Reinforcement, and Bayes, then the transition matrix is:

$$\mathbf{P} = \begin{bmatrix} P_{NN} & P_{NR} & P_{NB} \\ P_{RN} & P_{RR} & P_{RB} \\ P_{BN} & P_{BR} & P_{BB} \end{bmatrix}$$

and the steady state vector of long run probabilities,  $\mathbf{s} = [\mathbf{N} \ \mathbf{R} \ \mathbf{B}]$ , is the solution to:

$$(3) \quad \mathbf{s} = \mathbf{Ps} \quad \text{or} \quad [\mathbf{N} \ \mathbf{R} \ \mathbf{B}] \cdot \begin{bmatrix} P_{NN} & P_{NR} & P_{NB} \\ P_{RN} & P_{RR} & P_{RB} \\ P_{BN} & P_{BR} & P_{BB} \end{bmatrix} = [\mathbf{N} \ \mathbf{R} \ \mathbf{B}]$$

Pooling subjects together, for each of the 40 trials we estimate the transition probabilities as the proportion of the choices that transitioned to each state in the subsequent trial. For example, we estimate  $P_{RB}$  by counting the total number of trials where the subject left state R in the prior trial.

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<sup>10</sup> The authors thank Olivier L'Haridon for suggesting the Markov chain analysis.

Among those, the number of instances where state R was left for state B is  $P_{RB}$ , and so on for the other transition probabilities. Transitions into or out of a non-unique state where Bayesian and Reinforcement choices are aligned are discarded, which results in 1431 total state-transitions for the no-glucose subjects and 1393 total state-transitions for the glucose subjects. The calculated transition matrices are shown in the Supplementary Materials. The steady state probabilities are then found by solving (3), while using the constraint that the sum of the probabilities of being in any given state must equal 1.

The steady state probabilities are as follows:

$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=0} = [.245 \quad .357 \quad .398]$$

$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=1} = [.236 \quad .334 \quad .433]$$

Thus, the long-run steady state indicates that subjects will choose naively about 24% of the time. They will choose according to Reinforcement more often than Naïve, and Bayesian is the most likely choice state in the long-run. Glucose administration is found to decrease the probability of Reinforcement choice, slightly reduce the likelihood of Naïve choice, and increase the probability Bayesian choice. Specifically, the no-glucose subjects have a calculated steady probability of choosing Bayesian that is 4% higher than the probability of choosing based on Reinforcement. For the glucose-administered subjects, this difference is about 9%.

If we do a median split of subjects based on *Task IQ*, it may be of interest to separately examine steady state choice probabilities of those who seem to understand the task stimulus better than others. For those below the median *Task IQ* score, we have:

$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=0} = [.342 \quad .331 \quad .334]$$



$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=1} = [.349 \quad .320 \quad .334]$$

Not surprisingly, the low *Task IQ* subjects have an estimated probability distribution across states that is roughly uniform. This is consistent with the hypothesis that such subjects do not fully understand the stimulus. For those subjects with *Task IQ* above the median (those comprehending the task better), we have:

$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=0} = [.113 \quad .388 \quad .504]$$

$$[\mathbf{N} \quad \mathbf{R} \quad \mathbf{B}]_{\text{glucose}=1} = [.113 \quad .346 \quad .540]$$

As we would expect, these subjects have a much lower steady state probability of making a naïve choice (by virtue of our sample split), and Bayesian choices are somewhat more dominant in the steady state for these subjects. Again, the impact of glucose administration is apparent. The steady state probability calculations for no-glucose subjects indicate they are about 11% more likely to choose Bayesian over Reinforcement (50% compared to 39%), whereas this difference is about 19% for the glucose subjects. Glucose administration leads to an increase in the steady state probability of making the type of choice most indicative of deliberate “system 1” thinking, which is consistent with Hypothesis 2.

## Discussion

Our results provide new evidence on the effects of glucose and decision making in a task designed to separate Bayesian decision makers from those who follow a more simple reinforcement heuristic. A dual-systems approach led us to hypothesize that glucose, which fuels cognitive function and is particularly important in instances of cognitively demanding

tasks, would increase the proportion of Bayesian choices relative to a placebo (non-glucose) drink. We also hypothesized that reaction times, which are considered a barometer of system 2 thinking, would be longer for glucose-administered subjects given our prediction that glucose would increase effortful thought on the task.

With respect to reaction times, the data are consistent with our hypothesis. Reaction times are significantly longer on more difficult choice trials, *ceteris paribus*, which is consistent with the hypothesis of increased engagement of system 2 thinking on Hard trials. However, the glucose effect on reaction times is two-fold. Reaction times for glucose-administered subjects are estimated to be significantly longer initially, consistent with Hypothesis 2. We also find a significant glucose impact on learning, such that trend of improved reaction times across trials present in the placebo subjects is accelerated in the glucose subjects. Indeed, by the end of the 40 trial experiment, decision reaction times are estimated to be faster for glucose-administered subjects.

We also evaluate Bayesian errors, with particular attention to the fact that a significant number of decisions in the Easy trials are not Bayesian or Reinforcement consistent (indicating a lack of comprehension of the task, perhaps). Thus, we consider that subject choice may transition across three different states over the course of all trials: Naïve, Reinforcement, or Bayesian states. We then model transitions across states as a Markov process and we calculate that the steady state (long run) probability of making a Bayesian choice increases at the expense of Reinforcement choices in the glucose condition. This result indicates a beneficial glucose effect on overall quality of choice in the Bayesian task.

We have highlighted that the effect of glucose on decision making appears to focus on two dimensions of choice: reaction times and choice quality (Bayesian accuracy). Another key contribution of this paper is to show that glucose administration appears to beneficially impact cognitive efficiency or simple learning in this task, as represented by response times. A natural extension of this research is to examine the boundaries of this result as a function of one's glucose metabolism profile. Our task was completed by the subjects in approximately 30 minutes (i.e., 45 minutes after glucose consumption given that subjects wait 15 minutes after consumption before beginning the task). As such, subjects were likely at elevated glucose levels for the entire task (see Kennedy and Scholey, 2000). It is also the case that individual response to a given dosage of glucose may differ, and so future research might wish to directly measure baseline blood glucose levels of each subject prior to the start of the task.

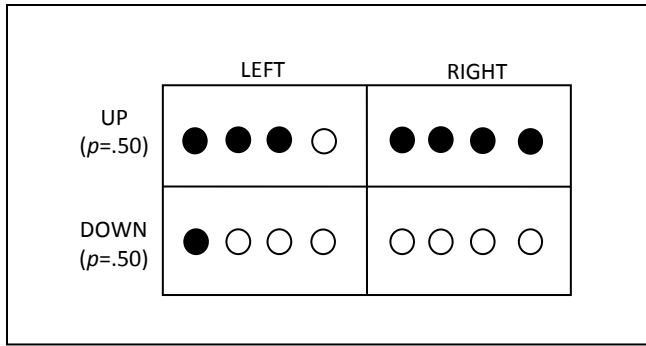
The implications of this research are potentially significant. For example, Danziger et al. (2011) find that Israeli parole board decisions are drastically different just before and after scheduled food breaks. While they suggest both glucose depletion and mental fatigue as hypotheses for the increase in unfavorable parole rulings just prior to food breaks (favoring the mental fatigue hypothesis, in the end), these two hypothesized effects likely interact. That is, favorable rulings are considered more difficult because they overturn the status quo, and evidence suggests the brain requires more glucose for difficult decisions (see our Section 1).<sup>11</sup> Thus, their two hypotheses are difficult to disentangle absent blood glucose measurements. Our results are, however, perfectly consistent with their findings. In our decision environment, glucose depleted subjects (the no-glucose subjects) are more likely to use a simple heuristic that

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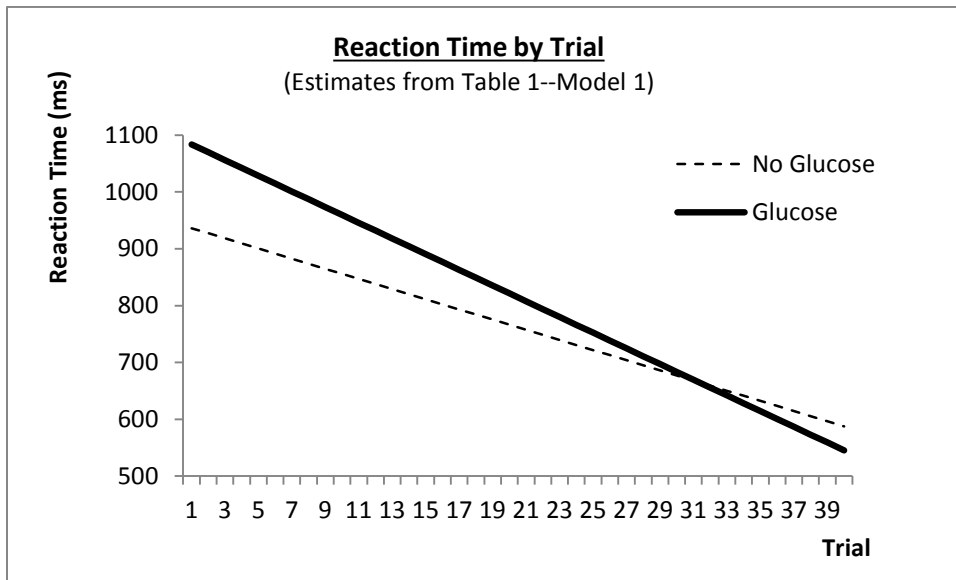
<sup>11</sup> Danziger et al (2011) highlight that decision times are significantly longer when parole is granted, which supports the hypothesis that overturning the status quo and granting parole is a more difficult decision.

biases decisions away from the higher expected value outcomes. A status quo bias in parole decisions may be a similarly attractive choice when one is glucose depleted, compared to the more difficult decision to overturn the status quo and grant parole.

The behavioral results of glucose administration also suggest that individuals with blood glucose regulatory disorders (hypo- or hyper-glycemic conditions) may manifest systematic differences in behavioral outcomes at different points in the blood glucose level cycle. Our subjects were normal young adults without such conditions, such that glucose administration would not produce blood glucose levels outside of the normal range. It is left for future research to assess whether individuals, such as diabetics, would manifest the same behavioral responses to glucose. It is also the case that some individuals habitually consume an ill-advised amount of sugar, and American society in particular is well-known for high levels of daily sugar consumption. For such individuals, it remains to be seen whether glucose deprivation would produce opposite results of our glucose administration treatment, or whether any of our results might differ for sensitive age groups like children or the elderly.



**FIGURE 1: Choice Task Stimulus**



**FIGURE 2: Reaction time by trial (Glucose vs. No Glucose)**

**TABLE 1:** Predictors of Reaction Times

**Reaction Times (in milliseconds)**  
random effects GLS estimation (113 groups)

Variable	Column 1	Column 2	Column 3
	Coeff (st. errors) All trials (n=4507)	Coeff (st. errors) Easy trials (n=2256)	Coeff (st. errors) Hard trials (n=2251)
constant	945.23 (41.58)***	923.94 (45.90)***	1020.69 (50.25)***
<i>Trial#</i>	-8.94 (1.08)***	-7.75 (1.49)***	-10.49 (1.53)***
<i>Hard Choice Trial (=1)</i>	47.25 (17.56)***	---	---
<i>Glucose (=1)</i>	152.40 (57.48)**	144.83 (64.63)**	144.07 (71.12)**
<i>Glucose*Trial</i>	-4.87 (1.51)***	-4.80 (2.09)**	-4.14 (2.14)**
<i>Chi-Squared test of model</i>	243.20***	98.13***	139.62***

\*, \*\*, \*\*\* indicate statistical significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test

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