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 response 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 response times. Glucose administration has a main effect of increasing response time, as predicted, but glucose also improves the marginal decrease in response 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

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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 intake 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 depict 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 appears exacerbated in middle-aged participants as compared to younger subjects. Such research highlights the importance in our current investigation to select a task that does 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 more deliberate thought processes as well.[1] For example, it has been argued that choice involving impulse control, which is an effortful cognitive endeavor, depletes blood glucose levels (see Gailliot & Baumeister, 2007, for a review) and research has also reported that supplemental glucose eliminates self-control impairments resulting from depleted glucose reserves (Gailliot et al, 2007).[2] Other research has shown that glucose administration improves patience for future rewards (Wang & Dvorak, 2010), which is consistent with a preferential impact of glucose on the same prefrontal brain regions that show increased activation when subjects choose delayed rewards over immediate payoffs (McClure et al, 2004).

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

[2] The results in Gailliot et al, 2007, are not without controversy, however, as noted in Kurzban (2010).

Much of aforementioned research suggests that task improvements are due to glucose metabolism fueling the thought processes needed for a task. However, an alternative hypothesis in the literature is that glucose serves as a signal or motivator of performance because it activates brain regions associated with motivation and reward response (Carter et al, 2004; Gant et al, 2010).[3] To evaluate this alternative model of glucose effects, several studies have used a protocol where the glucose drink is swished in the mouth but not consumed and therefore does not increase fuel to the brain. These studies report significant performance effects in the glucose-rinse conditions (e.g., Molden et al, 2012; Sanders et al, 2012; Hagger & Chatzisarantis, 2013) relative to an artificial sweetener condition, which is consistent with the hypothesis that the presence of glucose triggers additional motivation for task performance (physical or cognitive).[4] Kurzban (2010) also concludes that the existing evidence is more consistent with the hypothesis that glucose triggers reward motivation and central drive.[5] Though our results offer some insights into this debate (see Discussion section), our protocol was designed to examine the behavioral impact of glucose consumption, and therefore it was not intended to test the glucose metabolism versus reward signal theories.

Glucose Implications for Decision Making

This debate about glucose mechanisms notwithstanding, existing research (e.g., impulse control, time discounting, heuristics use) seems to indicate that glucose may preferentially impact executive function brain regions that are more active with deliberate thought. In the

[3] Indeed, there is also activation in the brain when one smells, tastes, and consumes food or drink (Kringelback, 2004).
[4] Kuhn et al (2013) describe much of this literature.
[5] Others have even found that one's beliefs about their state of will-power depletion are a significant determinant of their behavioral response to glucose (Job et al, 2013).

context of a dual-systems framework (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.[6]

Research has been consistent with this view that glucose administration will produce more system 2-consistent decisions. For example, Masicampo and Baumeister (2008) showed that glucose enriched subjects were less influenced by irrelevant auxiliary factors when forming preferences. Also, glucose administration reduced the use of stereotypes in another study (Gailliot et al, 2009)[7], and Wang and Dvorak (2010) find that glucose reduced preference towards immediate monetary reward over delayed payments. The results of each of these studies indicate that glucose is helpful in producing decisions that result from deliberate system 2 thinking, as opposed to allowing system-1 type decisions that are more automatic or based on heuristics.

Our study is most similar in spirit to McMahon and Scheel (2010). In their study subjects chose which of two events would occur in each of 200 decision rounds, and one event was set to occur more frequently (e.g., 70% of the time). This environment typically gives rise to "probability matching", whereby each alternative is selected with the same frequency as its occurrence, even though one should always select the more likely alternative to maximize expected payoffs. McMahon and Scheel found, counterintuitively, that glucose enriched subjects were actually *more* likely to probability match, while glucose deprived subjects more often used

[6] Neural evidence indicates that system 1 and system 2 thinking activate different parts of the brain (Goel et al 2000). A preferential glucose effect on system 2 thinking can be consistent with either a metabolic or reward motivation view of glucose mechanism.

[7] 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 cognitive resources (i.e., glucose depletion or sleepiness could both be considered a type of cognitive challenge).

the probabilistically optimal strategy. They attempt to reconcile this result by presenting some evidence that glucose enriched subjects engaged in normative rule generation of the sort requiring deliberate thought, which would imply that their results show that deliberate thought was enhanced by glucose. However, we note that their 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 response time (Kahneman, 2011). This leads to:

HYPOTHESIS 1: Glucose enriched subjects will have longer response 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 enriched 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 (29 males) were in the glucose enriched condition and 29 females (28 males) were in the artificial sweetener (i.e., no-glucose) placebo condition. 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, and each subject provided informed consent to participate.

Materials

Glucose manipulation. Prior to the experimental session a research assistant prepared lemonade drinks for the study. We used 12 oz. Minute Maid regular (40 g sugar) and diet Lemonade (0 g sugar) drinks to manipulate glucose levels and avoid caffeine interactions. 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. Though not the focus of the study, subjects rated the drinks after consumption on taste, perceived sweetness, and likelihood of purchase.

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. In Bayes rule terminology, the 50% choice of row would be base rate information, and the draw of a ball in stage 1 is the sample evidence. A Bayesian subject maximizing expected payoff will select the column in stage 2 that maximizes the probability of having a black ball drawn.

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 online Supplementary Materials), four practice trials 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-depleted state, and time-of-day is held roughly constant for all subjects (i.e., morning hours).

Sessions were conducted in a computer lab in groups of up to 9 subjects. After obtaining informed consent, participants were asked to consume their drink as quickly as possible. Afterwards, filler tasks were administered for 15 minutes, which included ratings of the drinks. In this way, we strictly control the latency after drink for all subjects and provide time for the glucose to adequately absorb into the bloodstream.[8]

[8] 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

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

Though assignment of condition was random and double-blind, subjects rated the "taste" $F(1, 113) = 6.97$, $p < .01$ partial $\eta 2 = .059$, and "sweetness" $F(1, 113) = 4.13$, $p < .05$ partial $\eta 2 = .036$ of the glucose drink significantly higher than that of the no-sugar drink. However, neither taste nor sweetness ratings were significant as regression co-variates (table 2A of online supplementary material), and so these perceptions are not driving our results. There was no significant difference in "likelihood of purchase" ratings between conditions $F(1, 113) = 1.16$, $p < .29$.

Unconditional Nonparametric Analysis

Response 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 response times are significantly higher in the glucose condition ($p < .01$), and the results hold for comparisons split by gender and task difficult ($p < .01$ 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 response times across all trials for a given subject, the Mann-Whitney tests only

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(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).

indicate a marginally significant decrease in *average* response 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 response 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).[9] Thus, the unconditional analysis shows some evidence indicating that glucose improves Bayesian accuracy on Hard trials. Alternatively, we

[9] This glucose effect on Hard trials is more significant for male subjects and is statistically insignificant for female subjects.

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 response 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 conduct a more proper analysis in the next section that takes this into account.

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 online supplemental material Table S1).[10] In focusing on glucose effects, we first analyze response time data using a random effects GLS estimation (indexed by subject and trial):

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

The results are shown in Table 1, column 1. The significant negative coefficient on *Trial* indicates that response times decrease across trials, ceteris paribus, which is evidence of a type of

[10] 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 $\textit{Bayes Error} = \alpha + \beta_1 \textit{Trial\#} + \beta_2 \textit{Hard Trial} + \beta_3 \text{Glucose} + \beta_4 (\textit{Glucose*Trial \#}) + \text{error}$
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 are available on request).

learning. Response 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 response 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 response 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 response time result is robust across trial difficulty.

This response time result is shown visually in Fig. 2. Thus, our results are consistent with Hypothesis 2—glucose will increase response times consistent with increased deliberate thought—but we estimate an additional glucose learning effect as proxied by response 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 fatigue and a movement towards automatic system 1 processing. However, results from analysis below are not consistent with this alternative interpretation.[11]

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

[11] Specifically, this is because our analysis will show that glucose improves Bayesian accuracy, and thus we have data indicating a pure effect of increased response times and increased accuracy due to glucose. This is also consistent with the initial nonparametric analysis we conducted which showed significantly increased response times and significantly improved Bayesian accuracy for glucose subjects. If the extra improvement in response 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.

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.[12] 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 as 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 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

[12] 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.

subjects are higher than those of the no-glucose subjects for the Bayes choice state (relative to Reinforcement state, in particular).[13]

Let $\boldsymbol{p_{ij}}$ 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, $\mathbf{s} = \begin{bmatrix} \mathbf{N} & \mathbf{R} & \mathbf{B} \end{bmatrix}$, solves:

$$(2) \qquad \mathbf{s = Ps} \quad \text{or} \quad \begin{bmatrix} \mathbf{N} & \mathbf{R} & \mathbf{B} \end{bmatrix} \cdot \begin{bmatrix} P_{NN} & P_{NR} & P_{NB} \\ P_{RN} & P_{RR} & P_{RB} \\ P_{BN} & P_{BR} & P_{BB} \end{bmatrix} = \begin{bmatrix} \mathbf{N} & \mathbf{R} & \mathbf{B} \end{bmatrix}$$

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. 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 (2), while using the constraint that the sum of the probabilities of being in any given state must equal 1.

[13] The authors thank Olivier L'Haridon for suggesting the Markov chain analysis.

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 of Bayesian choice. Specifically, the no-glucose subjects have a 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 2" 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 would increase outcomes reflective of system 2 thinking: longer response times and an increased proportion of Bayesian choices

With respect to response times, the data are consistent with our hypothesis. More difficult trials should engage more system 2 thinking and lead to longer response times (i.e., slow thinking), which we find. However, the glucose effect on response times is two-fold. Response times for glucose-administered subjects are estimated to be significantly longer than those for placebo subjects initially. But we also estimate a significant glucose effect across trials: response time improvements across trials among placebo subjects are accelerated in the glucose subjects. Indeed, by the end of the 40 trial experiment, response times are estimated to be faster

for glucose-administered subjects than for placebo-subjects. Glucose administration appears to beneficially impact cognitive efficiency or simple learning, as represented by response times in this task.

We also evaluate Bayesian outcomes by considering that subject choice may transition across three different states over the course of all trials: Naïve, Reinforcement, or Bayesian states. Transitions across states are modeled 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 quality/accuracy of choice.

Ours and others' glucose effect findings also suggest that those with hypo- or hyper-glycemic conditions may manifest systematic differences in behavioral outcomes, which suggests an interesting area for future research.[14] Another natural extension of this research would be to examine the boundaries of any identified result as a function of one's glucose metabolism profile. Our task was completed by the subjects in approximately 30 minutes (i.e., at 45 minutes after glucose consumption given that subjects wait 15 minutes after consumption before beginning the task). As such, subjects likely had elevated glucose levels for the entire task (see Kennedy & Scholey, 2000). It is also the case that individual response to a given dosage of glucose may differ. So, even though we followed a validated glucose administration

[14] Anecdotal evidence has been offered to suggest that hypoglycemia may be disproportionately present among those manifesting certain criminal or socially undesirable behaviors that imply lack of impulse control (Gailliot and Baumeister, 2007).

protocol[15], some of these more specific questions will require future research that perhaps directly measures blood glucose levels pre- and post-task.

The implications of this research are potentially significant. For example, Danziger et al. (2011) find that Israeli parole boards are much less likely to grant parole just before food breaks compared to just after them. While they suggest both glucose depletion and mental fatigue as hypotheses, and these hypotheses are difficult to disentangle in their data, their findings are suggestive. Favorable parole rulings are considered more difficult because they overturn the status quo, and evidence suggests the brain requires more glucose for difficult decisions.[16] Our results are consistent with their findings. In our decision environment, glucose depleted subjects (the placebo subjects) are more likely to use a simple heuristic that biases decisions away from the higher expected value Bayesian 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.

Finally, though our study was not intended to test the mechanism by which glucose impacts choice, it may offer some insights. First, studies favoring a glucose signal theory show a glucose-rinse effect only among ego-depleted subjects (e.g., Hagger & Chatzisarantis, 2013). Our subjects only completed non-depleting distractor tasks prior to the Bayes task, and so they would be considered non-ego-depleted. Further, our task is monetarily incentivized, such that our protocol should already engage brain reward centers for subjects in both conditions. This implies our results are consistent with the hypothesis that metabolized glucose is driving our

[15] McMahon and Scheel (2010) and Masicampo and Baumeister (2008) also implement glucose administration protocols absent glucose measurements.

[16] 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.

results.[17] While our results do not exclude the possibility of a glucose signal mechanism, the specifics of our design and results seem more consistent with the hypothesis that the additional metabolized glucose brain is what leads to the behavioral results we report.

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[17] Also, our results from drink ratings indicate that it is not the perceived taste or sweetness that impact response times. This particular null result is more consistent with a brain-fuel than a reward-signal hypothesis (see online supplementary material).

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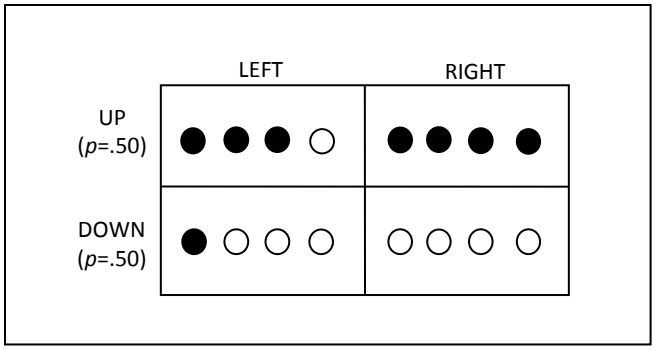


FIGURE 1: Choice Task Stimulus

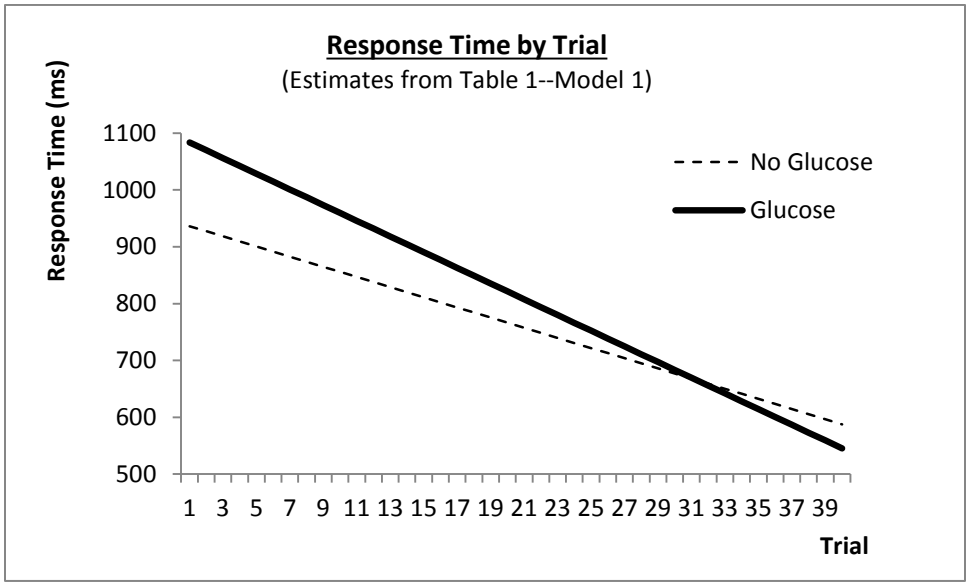


FIGURE 2: Response time by trial (Glucose vs. No Glucose)

TABLE 1: Predictors of Response Times

Response Times (in milliseconds)
random effects GLS estimation (113 groups)

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

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

ONLINE Supplemental Material: Analysis of response time data with additional co-variates

TABLE S1: Predictors of Response Times—GENDER included

Response Times (in milliseconds)
random effects GLS estimation (113 groups)

Variable	**Column 1** **Coeff (st. errors)** All trials (n=4507)	**Column 2** **Coeff (st. errors)** Easy trials (n=2256)	**Column 3** **Coeff (st. errors)** Hard trials (n=2251)
constant	965.14 (58.82)***	956.00 (65.04)***	1038.03 (72.47)***
Trial#	-9.71 (1.54)***	-8.60 (2.10)***	-11.70 (2.23)***
Hard Choice Trial (=1)	47.27 (17.55)***	---	---
Female (=1)	-38.14 (81.82)	-65.49 (92.57)	-30.51 (101.44)
Glucose (=1)	170.86 (81.00)**	119.50 (90.32)	187.60 (100.37)*
*Glucose*Trial*	-5.69 (2.12)***	-4.31 (2.90)	-5.28 (3.02)*
*Glucose*Female*	-42.64 (115.91)	53.28 (130.47)	-98.86 (143.70)
*Female*Trial*	1.50 (2.15)	1.78 (2.99)	2.24 (3.07)
*Female*Glucose*Trial*	1.86 (3.02)	-1.10 (4.19)	2.78 (4.30)
Chi-Squared test of model	246.26***	98.78***	143.13***

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

TABLE S2: Predictors of Response Times—TASTE and SWEETNESS variables included

Response Times (in milliseconds)
random effects GLS estimation (113 groups, n=4507 trials)

Variable	Column 1 Coeff (st. errors)	Column 2 Coeff (st. errors)	Column 3 Coeff (st. errors)
constant	991.87 (88.88)***	945.05 (106.64)***	966.75 (127.94)***
Trial#	-8.96 (1.08)***	-8.96 (1.08)***	-8.96 (1.08)***
Glucose (=1)	155.16 (59.00)***	149.25 (58.50)***	152.89 (59.78)***
Taste	-7.58 (26.48)	---	-8.29 (26.71)
Sweetness	---	6.61 (26.91)	7.42 (27.15)
*Glucose*Trial*	-4.83 (1.51)***	-4.83 (1.51)***	-4.83 (1.51)***
Chi-Squared test of model	235.72***	235.70***	235.80***

*,**,*** indicate statistical significance at the .10, .05, and .01 levels, respectively, for the 2-tailed test.
Sweetness and Taste are self-reported on a scale of 1-5 with higher number indicating better taste or more sweet as perceived by subjects after drink consumption.

Results in Table S2 are qualitatively and quantitatively similar if estimating the model for only the subset of Easy or Hard choices. Statistical significance is similar in every way to full sample results shown above (results available upon request).

ONLINE Supplemental Material: Markov Transition Matrices

Transition Matrices for discrete regular Markov chain analysis.

Transition matrix defined as $\boldsymbol{P} = \begin{bmatrix} P_{NN} & P_{NR} & P_{NB} \\ P_{RN} & P_{RR} & P_{RB} \\ P_{BN} & P_{BR} & P_{BB} \end{bmatrix}$ where *N, R, B* refer to Naïve, Reinforcement, and Bayesian choices, respectively. P_{XY} refers to a choice transition out state X and into state Y.

Glucose=0: $\boldsymbol{P} = \begin{bmatrix} .26 & .36 & .38 \\ .23 & .44 & .33 \\ .25 & .28 & .47 \end{bmatrix}$ **Glucose=1:** $\boldsymbol{P} = \begin{bmatrix} .30 & .38 & .33 \\ .25 & .37 & .38 \\ .19 & .28 & .53 \end{bmatrix}$

Subjects *below* median in TaskIQ (i.e.,subjects who were naïve on > 7 of 20 Easy trials)

Glucose=0: $\boldsymbol{P} = \begin{bmatrix} .28 & .36 & .36 \\ .34 & .38 & .27 \\ .41 & .25 & .34 \end{bmatrix}$ **Glucose=1:** $\boldsymbol{P} = \begin{bmatrix} .32 & .35 & .34 \\ .37 & .34 & .29 \\ .36 & .27 & .37 \end{bmatrix}$

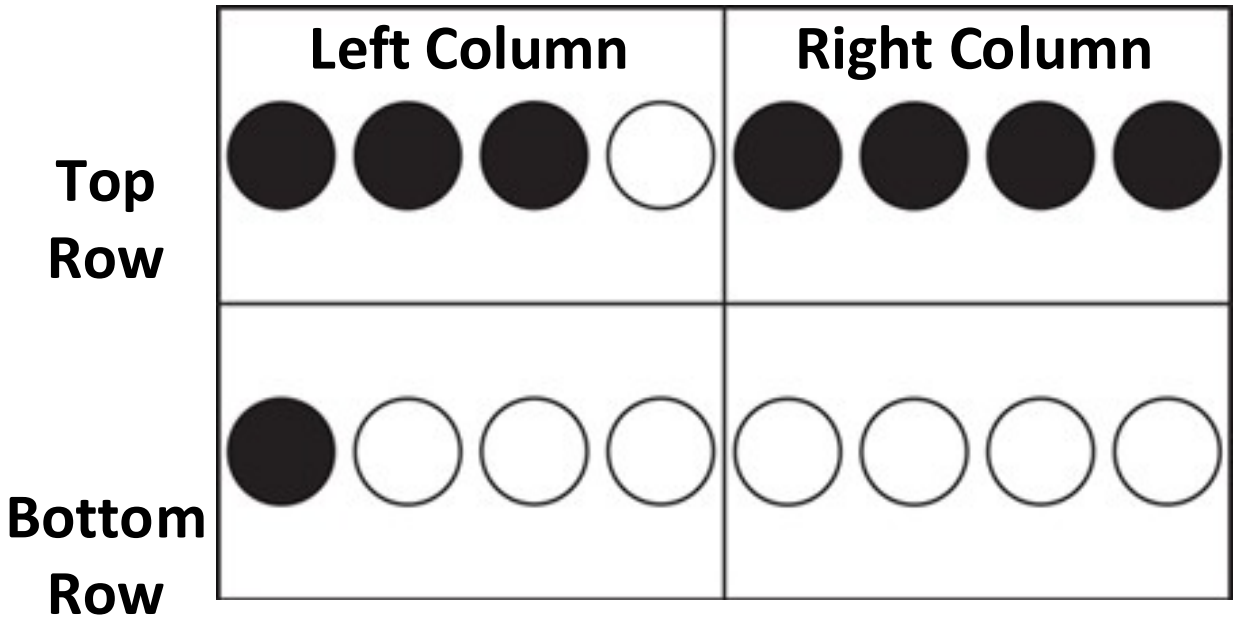
Subjects *above* median in TaskIQ (i.e.,subjects who were naïve on ≤ 7 of 20 Easy trials)

Glucose=0: $\boldsymbol{P} = \begin{bmatrix} .17 & .39 & .44 \\ .09 & .50 & .41 \\ .11 & .30 & .59 \end{bmatrix}$ **Glucose=1:** $\boldsymbol{P} = \begin{bmatrix} .22 & .50 & .28 \\ .13 & .40 & .47 \\ .08 & .28 & .64 \end{bmatrix}$

ONLINE Supplemental Material: Task Instructions

EXPERIMENTAL INSTRUCTIONS

(screen shots of computerized instructions)



In this task, there will be a series of decision rounds. Each round has 2 stages. In each stage, a ball will be drawn from one of the four cells in the 2x2 box above. The following slides contain additional instructions and provide examples of the stages. After these slides, you will complete four practice rounds. You will then have an opportunity to ask any questions before beginning the actual task.

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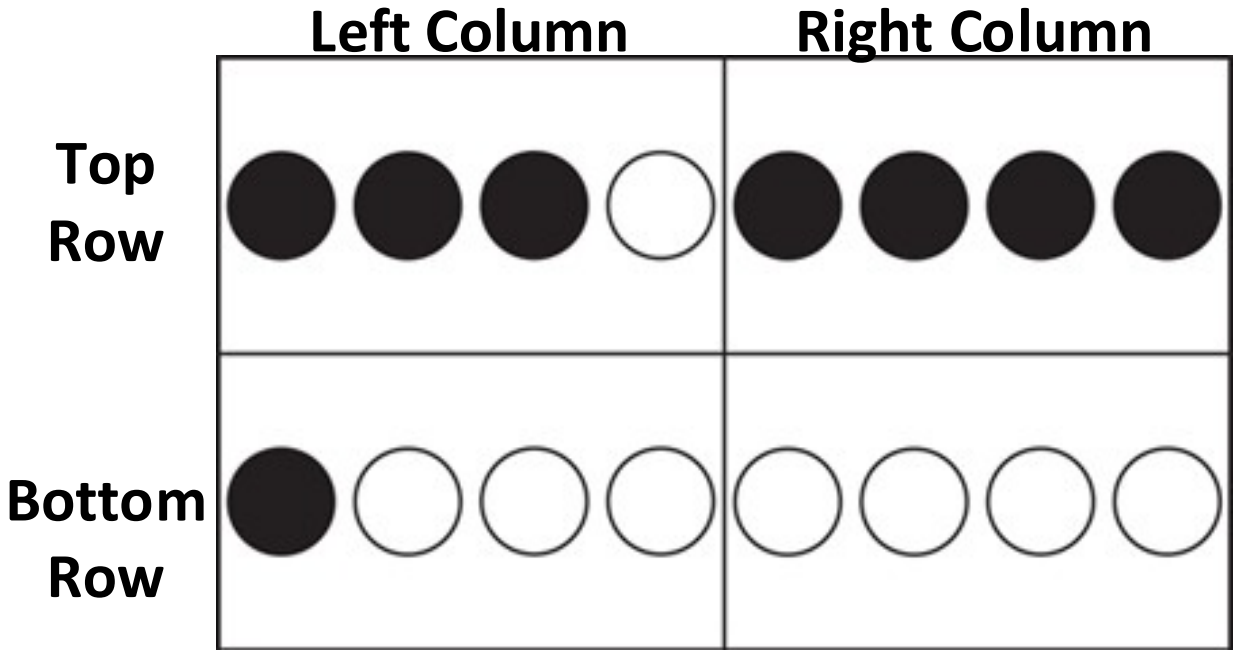
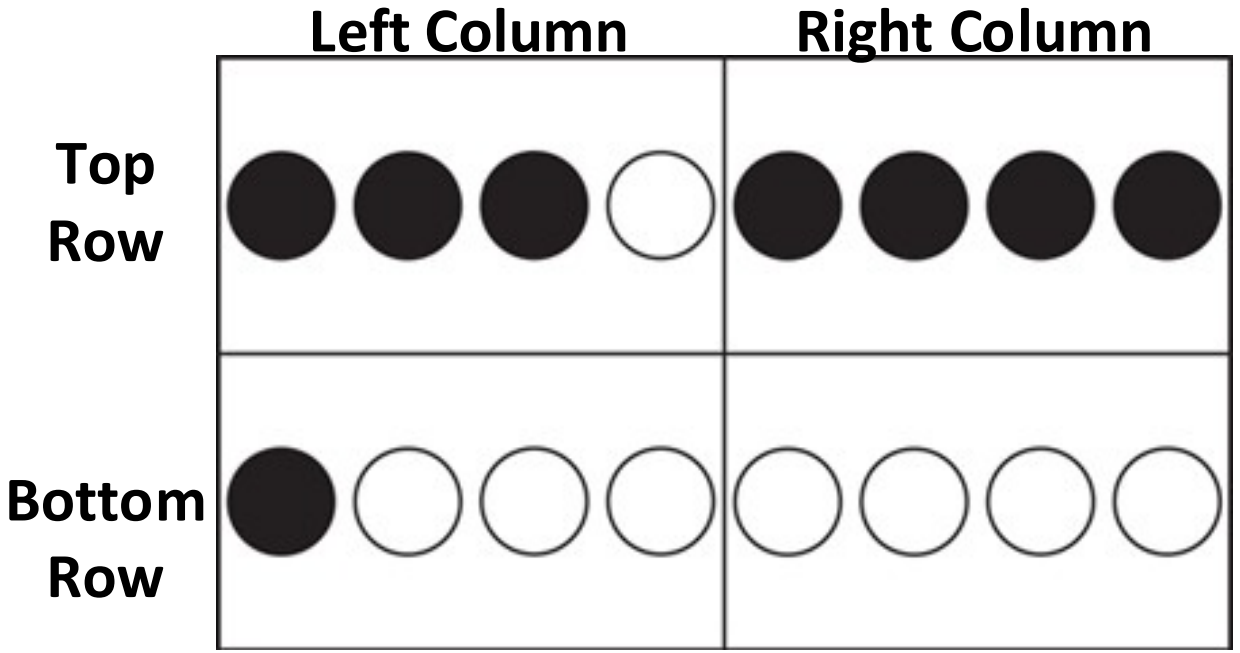


At the beginning of each round, the computer flips a fair coin to select either the TOP or the BOTTOM row. You will not receive feedback on the results of the coin toss. After the top or bottom row is selected, it will remain the same for both Stage 1 and Stage 2 of that round. The row only resets for each new round.

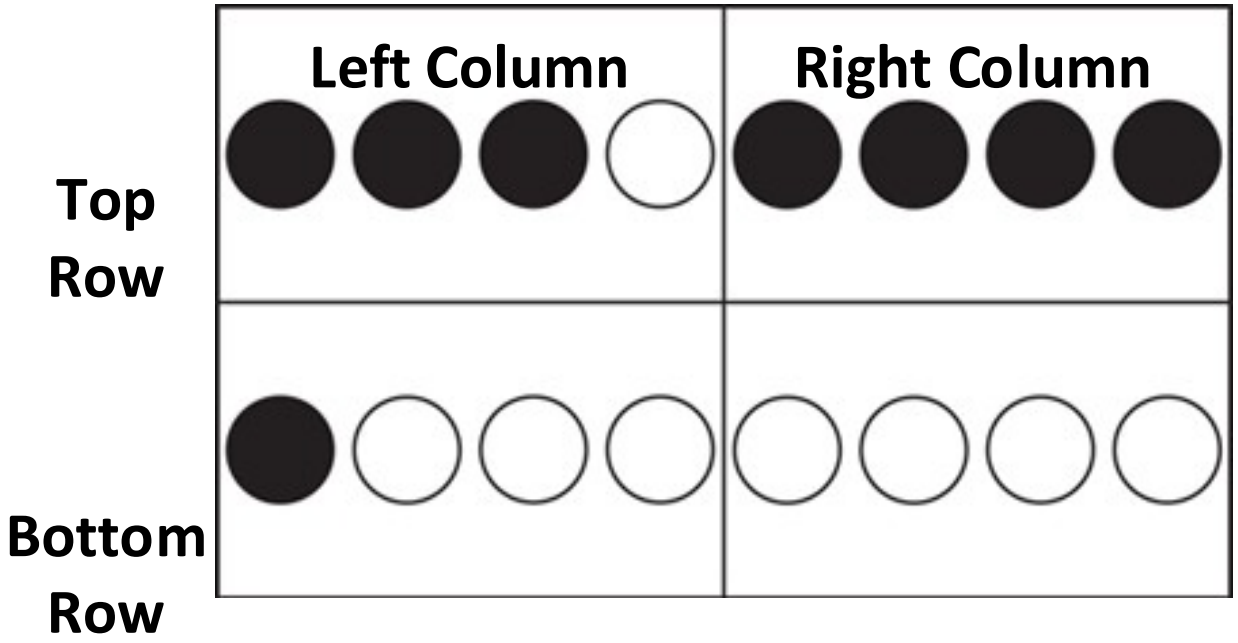
Press SPACEBAR to continue



In Stage 1, the computer will randomly select either the LEFT or the RIGHT Column. You will be told which column is selected. A ball will then be drawn from the selected cell (i.e., the cell resulting from the Stage 1 column choice, which you are told, and the row chosen for both stages of that round, which you are not told). After the drawing, the ball is replaced so that the contents of each cell are always the same (i.e., contents are always exactly as shown in the picture of the 2x2 box).

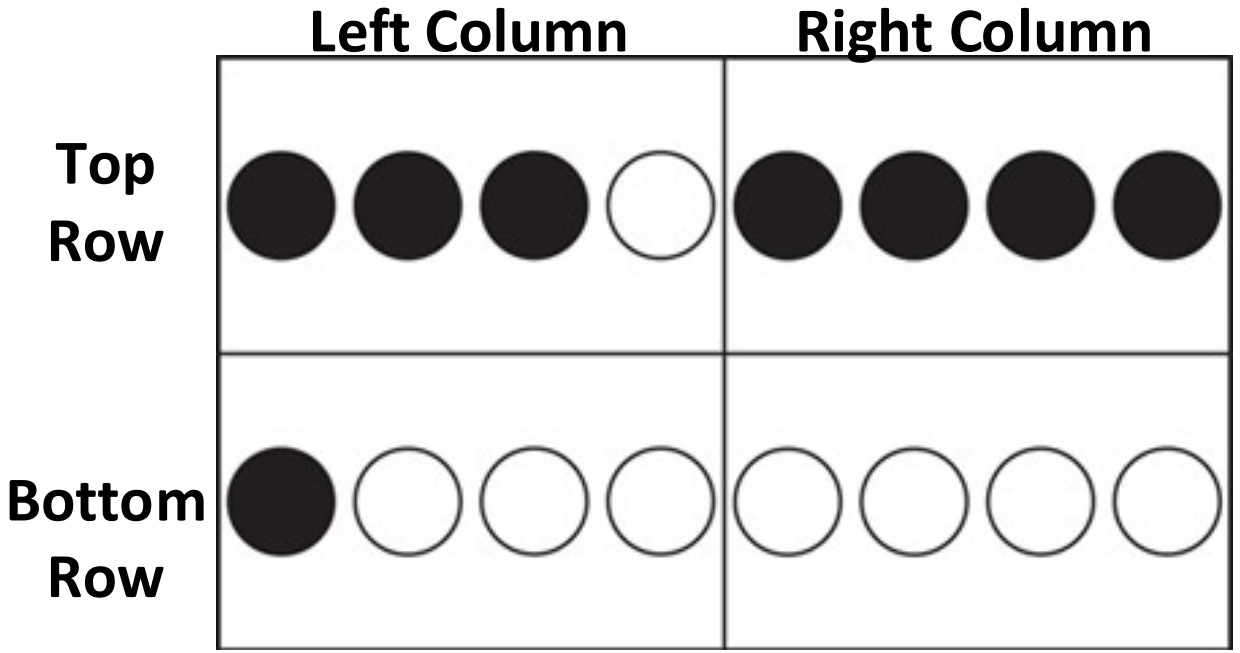
Press SPACEBAR to see an example of Stage 1.

Stage 1 Example



The computer chose the LEFT/RIGHT column. A WHITE/BLACK ball was drawn.

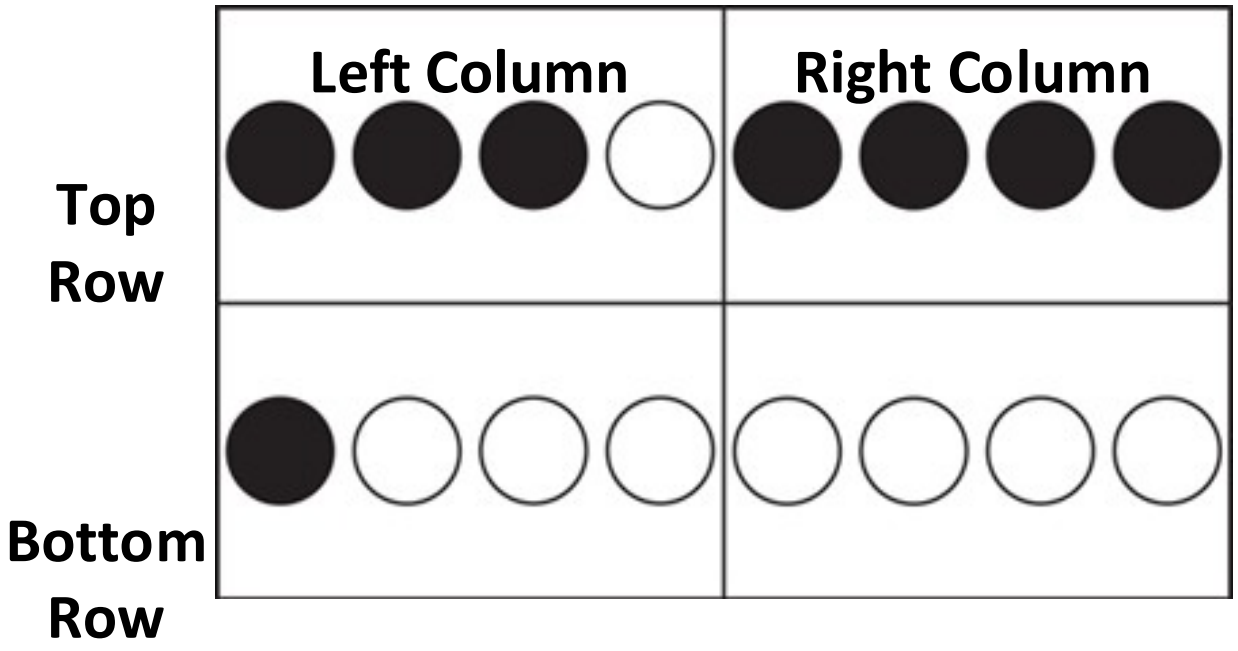
(Press SPACEBAR to continue with the instructions.)



In Stage 2, your task is to choose the column you prefer and another ball is drawn and replaced afterwards. If a BLACK BALL is drawn from the resultant cell in Stage 2, you will earn $10. As such, your Stage 2 choice affects the likelihood of you earning $10. You may choose the same column that the computer picked in Stage 1 or you may choose the other column.

Press SPACEBAR to see an example of Stage 2.

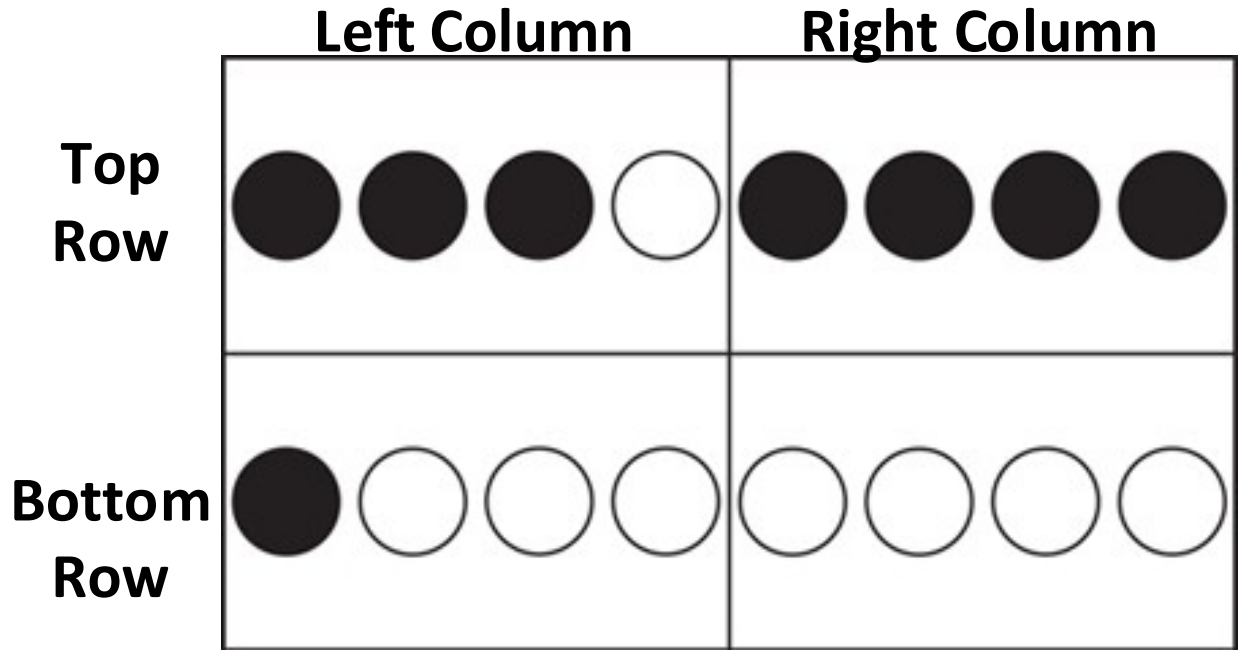
Stage 2 Example



Choose a column.

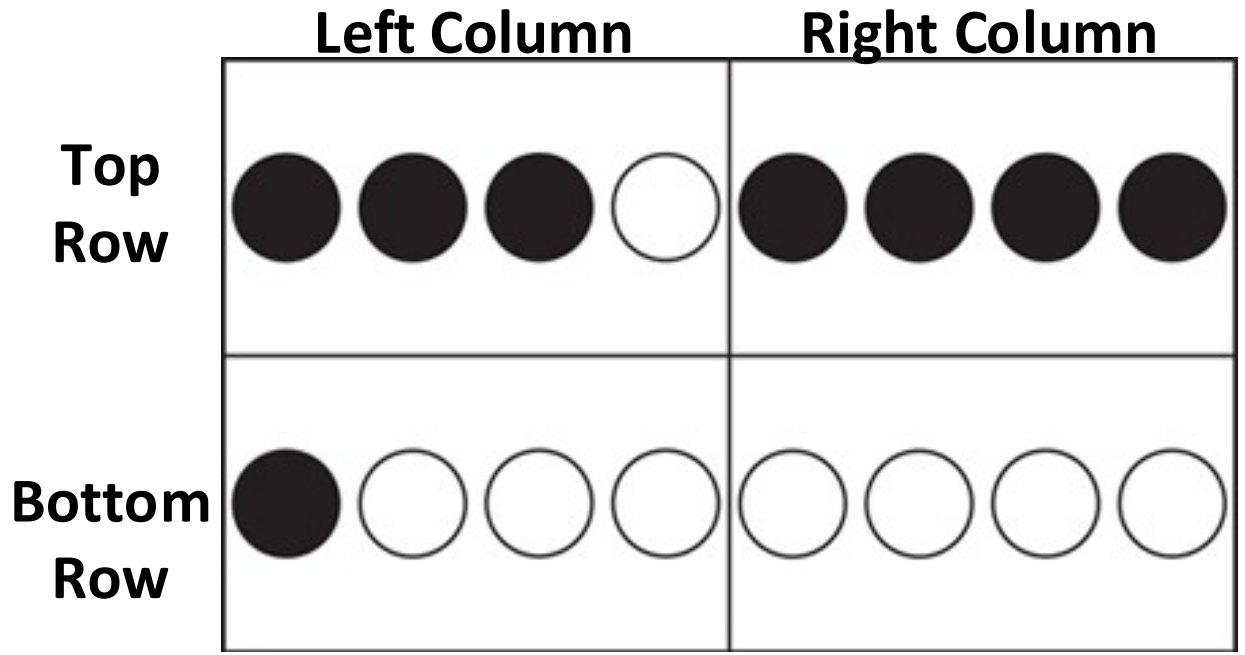
Press the LEFT arrow for the LEFT column. Press the RIGHT arrow for the RIGHT column.

(Press SPACEBAR to continue with the instructions.)



Remember, at the beginning of each round, the row (TOP or BOTTOM) chosen by the coin toss remains fixed for both Stage 1 and Stage 2 of that round. You will make your selection using the arrow keys. Press the LEFT ARROW for the left column, or press the RIGHT ARROW for the right column in Stage 2. Each round is timed and you will only have 6 seconds to choose the column. Failure to make a choice implies you cannot earn $10 for that round.

Press SPACEBAR to continue.



The computer will record your Stage 2 response and you will be compensated based on the results of the Stage 2 drawing in the following manner. At the end of the experiment, the computer will randomly select one round from among all the rounds of this task. Each round has an equal chance of being selected. The ball drawn in Stage 2 of the selected round will determine your payoff in this task. If a black ball is drawn, you will receive $10. If a white ball is drawn, you will receive nothing. Also, if the round randomly chosen is a round in which you failed to respond, you will receive nothing.

Press SPACEBAR to continue

Remember:

- For each round, a row will be chosen but you will not be told which one

- For each round, the row chosen remains fixed for both Stage 1 and Stage 2

- In Stage 1, the computer selects the column and a ball is drawn based on the selection

- You choose the column in Stage 2 and a ball is drawn based on your choice

- The ball is replaced after each drawing, so the box contents are always the same

- A payoff of $10 is ONLY awarded for a black ball drawn in Stage 2 of a randomly selected round

- If a white ball is drawn in Stage 2 of the randomly selected round, or if you failed to respond, you receive nothing

Press SPACEBAR to continue