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
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Abstract

This study explored metabolic mechanisms of future (delay) discounting, a choice phenomenon where people value present goods over future goods. Using fluctuating blood glucose as an index of body-energy budget, optimal discounting should regulate choice among rewards as a function of temporal caloric requirement. We identified this novel link between blood glucose levels measured in the lab and future-discounting rates of participants, who made choices between a “smaller and sooner” reward and a “larger but later” option, with possible actual monetary rewards. A group of participants who drank a soft drink that contained sugar showed a reduced rate of future discounting afterward, when we controlled for sex, age, body mass index, and the taste of the drink. In contrast, a group of participants who drank a soft drink that contained artificial sweetener showed an increased rate of future discounting. Blood glucose levels not only varied as a result of caloric intake but also regulated the rate of future discounting, according to participants’ dynamic body-energy budget.

Keywords

intertemporal choice, future (delay) discounting, blood glucose

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These high wild hills and rough uneven ways,
 Draw out our miles and make them wearisome;
 But yet your fair discourse hath been as sugar,
 Making the hard way sweet and delectable.

—William Shakespeare (from *Richard II*, Act II, Scene III)

Would a grain of sugar itself, instead of a Shakespearean metaphor, make one’s expected future sweeter? Would the mind read fluctuating blood glucose levels? Would a person’s daily body-energy budget affect his or her evaluation of future rewards?

Surprisingly little is known about how fluctuating blood glucose levels affect cognitive functions. From a perspective of body-energy regulation, we examined how the daily fluctuation of blood glucose levels regulates evaluation and choice of present versus future rewards, as measured by future, or delay, discount rate. People discount the future when they value present goods over future goods and when they prefer a smaller and sooner reward to a larger but later reward (Ainslie, 1975; Frederick, Loewenstein, & O’Donoghue, 2002; Soman et al., 2005).

Our exploration of the interplay between the body (fluctuation of blood glucose levels) and the mind (future discounting) was informed by three theoretical approaches: evolutionary psychology, life-history theory, and risk-sensitive foraging models. Evolutionary psychologists argue that selection should favor allocations of effort depending on how quickly the expected utility or fitness declines over time. Thus, the

higher the body-energy budget, the more affordable future-oriented actions are to the organism.

Life-history theory assumes that individuals make specific trade-offs at different times in life (Kaplan, Gangestad, & Buss, 2005; Wang, Kruger, & Wilke, 2009). Future discounting thus should be adjusted to both actual life expectancy of a population and individual subjective life expectancy (e.g., Read & Read, 2001; Wang et al., 2009). Similarly, at a physiological level, daily changes in energy consumption and expenditure, as indicated by blood glucose levels, should also provide a dynamic weighting scale for evaluating immediate versus future returns.

According to risk-sensitive foraging theory (Stephens & John, 1986), organisms regulate their degree of risk taking according to their dynamic body-energy condition, to maximize the chance of reaching daily energy requirements and at the same time minimize the probability of an energy shortfall. Based on an energy-budget rule (Kacelnik & Bateson, 1997; Real, 1991; Wang, 2002), we hypothesize that when the status quo (i.e., body-energy budget) is positive or increasing, organisms should be, on average, more future oriented, to increase the chance of reproductive success. However, when

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the status quo is negative or decreasing, organisms should value present resources more than future resources, to avoid survival-threatening consequences. In general, optimal future discounting should regulate choice among rewards as a function of temporal caloric requirement.

In contrast to the energy-budget-regulation hypothesis, an equally plausible alternative is a model in which cognitive resources are based on self-regulatory strength (Dvorak & Simons, 2009; Gailliot et al., 2007). Baumeister, Bratslavsky, Muraven, and Tice (1998) have proposed that impulsive action may be a result of depleted self-regulatory abilities. As such, the choice of a small reward now over a larger reward in the future may be due to depleted resources. In fact, research has shown that making difficult choices depletes effortful resources (Vohs et al., 2008) and these resources can be restored by increasing blood glucose (Gailliot & Baumeister, 2007). This suggests that this resource may rely on energy consumed during processing.

Accordingly, the future is more abstract than the present and thus may require more energy to process. Blood glucose as brain fuel would strengthen effortful cognitive processing for future events. However, when glucose levels are low, people would be less able to cognitively process, so present rewards may seem worth more than future rewards because of cognitive errors. This alternative hypothesis is in line with recent work by Masicampo and Baumeister (2008), which showed that decision biases can be induced by depleting cognitive resources.

Method

Participants

Participants were 65 undergraduate students who received course credit for participation. There were 32 participants (19 females and 13 males) in the experimental condition and 33 participants (22 females and 11 males) in the control condition. Participants' ages ranged from 19 to 51 years ($M = 23.1$, $SD = 4.5$).

Measures

Future discounting was assessed by 14 choice options. Seven of the choice options were presented before the experimental manipulation, and 7 after the experimental manipulation. Participants were presented with two monetary options and shown actual money in two separate piles. Participants were asked questions such as, "Would you prefer \$120 tomorrow or \$450 in 31 days?" To encourage accurate responding, participants were told they would roll dice at the conclusion of the study for the opportunity to win one of their actual choices. Their responses were used to compute discounting parameters before and after the experimental manipulation, as the dependent measure.

Apparatus

Blood glucose was measured using a ReliOn Ultima (Abbott Laboratories, Abbott, IL) blood glucose monitor. Participants

were informed of the blood glucose measurement during recruiting and were instructed to not eat before the experiment.

Procedure

Participants were randomly assigned to condition before their arrival at the lab. Upon arrival, they completed informed-consent forms and supplied demographic information. Their height and weight were then assessed, to compute body mass index, using the following formula: $(\text{weight in pounds} \times 703) / \text{height}^2$ (in inches). Next, the first blood glucose check (Time 1; T1) was completed, followed by the initial future-discounting task. Participants then consumed a caffeine-free soda, which contained either sugar (Sprite; experimental condition) or an artificial sweetener (Sprite Zero; control condition). All participants were unaware of the type of soda. Immediately after consumption, participants rated the pleasantness of the soda on an 11-point scale ranging from 1, *very unpleasant*, to 11, *very pleasant*. After a 10-min break in which each participant answered other questions for a different study (life expectancy, ratings of likelihood of engaging in different risky behaviors, school performance and goals, and risk-choice questions), participant's blood glucose was again assessed (Time 2; T2). They then completed the final future-discounting task and were debriefed. After completing all tasks, participants rolled two standard dice, and anyone who threw double ones or sixes were paid in the form of a check postdated to the appropriate delay, based on one of his or her randomly selected intertemporal choices.

Measuring individual discount parameters

We modified Wilson and Daly's (2004) method by using money instead of computer displays. We gave participants two choices: a specified sum "tomorrow" or a larger sum (14 choices ranging from \$90 to \$570) after a specified delay (range of 4 to 939 days). Seven pairs were given before, and 7 pairs after, the experimental manipulation (consumption of a soft drink that contained either sugar or aspartame).

Although classic research on delay discounting in economics and finance assumes an exponential function, people and animals typically behave as though they discount near futures at higher rates than more distant futures, so that experimentally assessed discount rates approximate a hyperbolic, rather than exponential, function of delay (e.g., Frederick et al., 2002; Green & Myerson, 2004; Loewenstein & Prelec, 1992). Thus, in our measure of future discounting, indifference between a smaller, earlier reward (tomorrow) and a larger, later reward (future) indicates the following hyperbolic discount parameter k (Kirby & Marakovic, 1996; Wilson & Daly, 2004): $k = (\text{future \$} - \text{tomorrow \$}) / [(\text{days of delay} \times \text{tomorrow \$}) - (\text{future \$})]$. More detailed method and results sections are provided in the Supplemental Material available on-line.

Results

Univariate and bivariate analyses of control variables

A Levene's test of homogeneity of variance was significant for the T2 discounting parameter; thus, we performed a natural log transformation on the discounting parameters to normalize the variable distributions. Following the transformation, the Levene's tests for both T1 and T2 discounting parameters were nonsignificant. There were no differences in gender distribution across conditions, $\chi^2(1, N = 65) = 0.37, p_{\text{rep}} = .46$. Nor were there differences between the control and experimental conditions in other participant variables, such as age (control $M = 23.61, SD = 5.88$; experimental $M = 22.56, SD = 2.50$), $t(63) = 0.93, p_{\text{rep}} = .74$, and body mass index (control $M = 23.75, SD = 3.92$; experimental $M = 24.85, SD = 5.17$), $t(63) = 0.97, p_{\text{rep}} = .66$. Experimental factors also did not differ between groups, including pleasantness ratings of the drink (control $M = 5.42, SD = 2.02$; experimental $M = 5.19, SD = 2.29$), $t(63) = 0.44, p_{\text{rep}} = .34$; T1 blood glucose levels (control $M = 98.58, SD = 12.95$; experimental $M = 94.41, SD = 11.33$), $t(63) = 1.43, p_{\text{rep}} = .83$; and the natural log of T1 future discounting (control $M = -6.26, SD = 1.61$; experimental $M = -6.11, SD = 1.32$), $t(63) = 0.43, p_{\text{rep}} = .33$. There was a small but significant decrease from T1 blood glucose ($M = 98.58, SD = 12.95$) to T2 blood glucose ($M = 94.39, SD = 12.18$) in the control condition, $t(32) = 3.32, p_{\text{rep}} = .998$, Cohen's $d = 0.58$. In contrast, there was a considerable increase from T1 blood glucose ($M = 94.41, SD = 11.33$) to T2 blood glucose ($M = 125.28, SD = 22.95$) in the experimental condition, $t(31) = 8.40, p_{\text{rep}} > .999$, Cohen's $d = 1.49$. As predicted, an analysis of covariance (ANCOVA), controlling for T1 blood glucose, showed T2 blood glucose was significantly higher in the experimental condition than in the control condition, $F(1, 62) = 77.90, p_{\text{rep}} > .999, \eta_p^2 = 0.56$.

Primary analyses

We conducted an ANCOVA, with condition as the between-subjects factor and the natural log of the discounting parameters at T1 and T2 as the within-subjects factor. Gender, T1 blood glucose, time of day, and pleasantness of the drink were added as covariates, to rule out possible effects of these factors on future discounting due to gender differences in metabolism, the length of fasting, or mood-dependent choice preference. As predicted, there was a significant interaction between condition and time (i.e., T1 future discount to T2 future discount), $F(1, 59) = 15.61, p_{\text{rep}} > .999, \eta_p^2 = .21$. This was the only significant predictor in the model. As depicted in Figure 1, there was a decrease in future discounting after participants drank a soft drink containing sugar, $t(31) = 2.55, p_{\text{rep}} > .95$, Cohen's $d = 0.45$, but an increase in future discounting after participants drank a soft drink containing aspartame, $t(32) = 3.12, p_{\text{rep}} > .99$, Cohen's $d = 0.54$.

We also conducted an observed variable path analysis using Mplus (Version 5.21; Muthén & Muthén, 2009) with

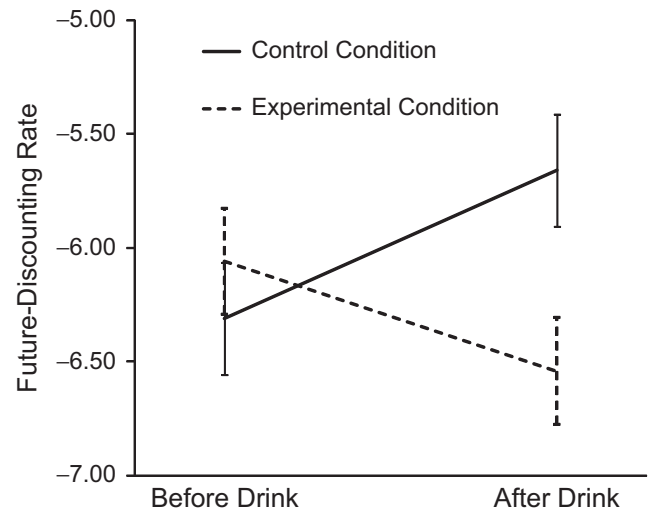


Fig. 1. Participants' future-discounting rates as a function of condition and timing relative to consumption of the beverage. Members of the experimental condition consumed a soft drink that contained sugar; members of the control condition consumed a soft drink that contained aspartame. Before and after consuming the soft drink, participants completed a future-discounting task, in which they answered questions such as, "Would you prefer \$120 tomorrow or \$450 in 31 days?" We performed a natural log transformation on the responses, to normalize the distributions. Response values ranged from -9.21 to -2.94 . Lower values signify less discounting of future reward. Error bars represent 95% confidence intervals of the mean future-discounting rates within each group at the two separate time points.

maximum likelihood estimation (see Fig. 2). T2 future discounting was specified as the endogenous variable, T2 blood glucose as the mediator variable, and condition and body mass index as exogenous variables. T1 blood glucose and future discounting were added as exogenous covariates on their respective T2 endogenous criteria. The model showed excellent fit of the data, $\chi^2(4) = 2.77, p_{\text{rep}} = .40$, comparative fit index = 1.00, root-mean-square error of approximation = .00, standardized root-mean-square residual = .035.

Condition was positively associated with T2 blood glucose. T2 blood glucose was negatively associated with T2 future discounting. The model shows that the effect of condition on T2 future discounting was fully mediated by change in blood glucose; thus, the observed difference in T2 future discounting between conditions was due solely to the experimental manipulation on blood glucose. As shown in Figure 3, the hyperbolic discounting curves at T2 between the two conditions were markedly different, with the control condition having a steeper discounting rate.

Discussion

Our results showed that human preferences for future versus current rewards fluctuated from moment to moment based on blood glucose levels. As actually measured in the lab, increasing blood glucose levels via a soft drink containing sugar led to an increase in the value placed on future rewards. In

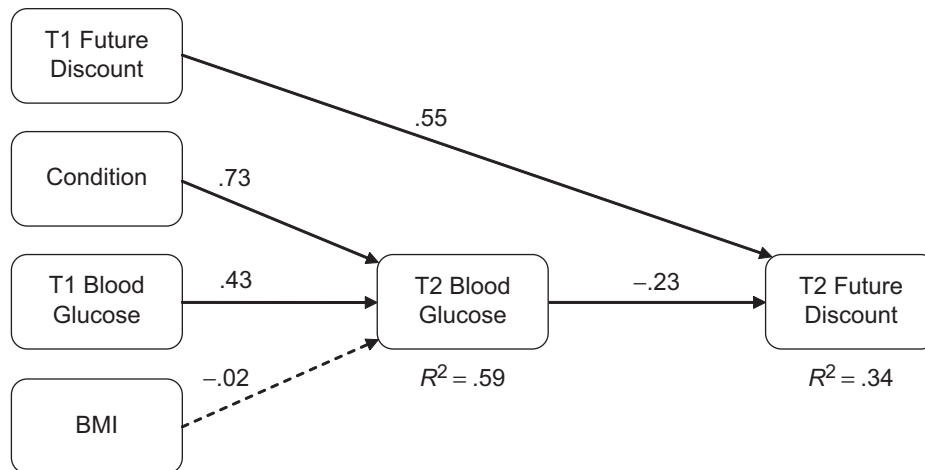


Fig. 2. Results of the path analysis of change in blood glucose from Time 1 (T1) to Time 2 (T2) as a mediator of the effects of body mass index (BMI), condition (experimental vs. control), and future discounting at T1 on future discounting at T2. Paths represented by solid lines were significant at $p_{\text{rep}} > .95$. R^2 values represent variance accounted for in T2 blood glucose and T2 future discounting, respectively.

contrast, drinking a soft drink that did not contain sugar led to an increase in the value placed on current rewards. These findings suggest an adaptive mechanism linking human decision making to metabolic cues, indicating environmental scarcity on a micro level. Moreover, artificial sweeteners may alarm the body by giving a perception of a caloric crisis, leading to increased body weight and obesity. In a recent study, Swithers and Davidson (2008) showed that rats eating sweet, noncaloric substances increased food intake and reduced energy expenditure. Contrary to the advertised notion that sugar-free products are the key to weight loss, one study found that humans who

consumed artificial sweeteners gained more weight than those who did not (Stellman & Garfinkel, 1986). Similarly, DeCesare and Honey (2009) found that participants who drank a drink containing sugar showed a smaller blood glucose response than participants who drank a drink that contained an artificial sweetener, which suggested that artificial sweeteners may disrupt body metabolism by altering responses to sweet foods that do contain calories.

Although not predicted, an energy-budget regulation model can account for the observed increase in participants' future-discounting rate after they consumed a soft drink that

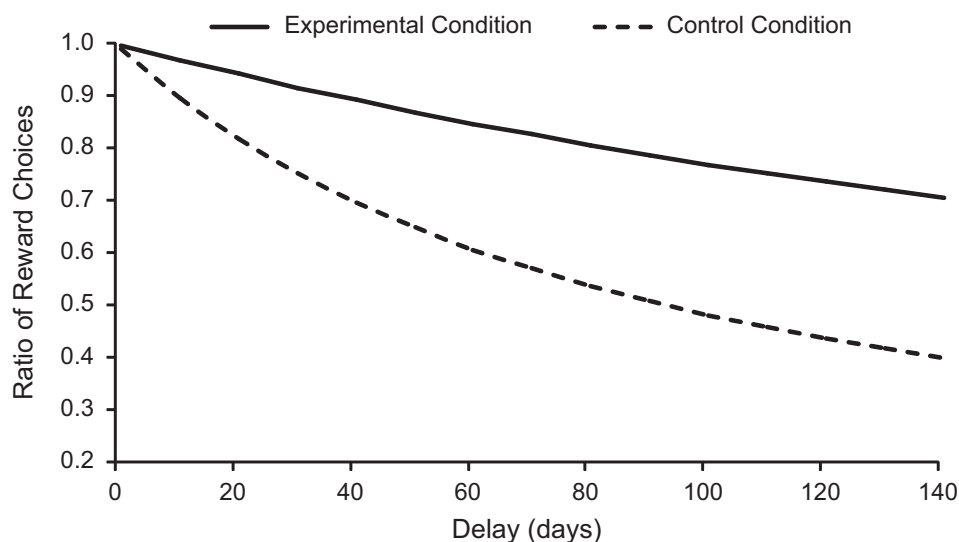


Fig. 3. Ratio of participants' reward choices (smaller and sooner rewards/larger and later rewards) as a function of experimental condition and length of delay. Members of the experimental condition consumed a soft drink that contained sugar; members of the control condition consumed a soft drink that contained aspartame. The choice ratio was calculated as $1/(1 + k * \text{delay})$, where k is the future-discounting parameter derived from the choice data.

contained aspartame, as a response to a detected caloric problem due to the use of artificial sweetener. However, it would be more difficult for a cognitive resource model to account for this finding. Future research should continue to distinguish these two mechanisms in intertemporal choice.

In a recent article, Briers, Pandelaere, Dewitte, and Warlop (2006) argued that people's desire for money is a modern derivative of their desire for food. In accordance with this argument, they showed that hungry people were less likely than satiated people to donate to charity. Helping behaviors appear to be regulated in part by glucose levels (see DeWall, Baumeister, Gailliot, & Maner, 2008; Gailliot et al., 2007). People often help in hopes of future reciprocity. Perhaps low blood glucose undermines current helping because future reciprocity is more discounted.

A variety of studies in the literature have suggested that there are many ways to influence future discounting and intertemporal choice in relation to such topics as personality traits, including impulsivity (see Frederick et al., 2002); situational variables, including mating cues (Wilson & Daly, 2004); physiological factors, including drug intoxication (Kirby, Petry, & Bickel, 1999); and brain structure (e.g., McClure, Laibson, Loewenstein, & Cohen, 2004). This study adds to the list a metabolic mechanism of using daily fluctuating blood glucose levels as cues in regulating body-energy balance and its behavioral manifestation in future discounting. If regulating blood glucose levels can affect delay (future) discounting, reducing the degree of fluctuation in blood glucose may offer a possible means for the treatment and intervention of some impulsive behaviors, as seen in compulsive and impulsive disorders, anorexia, drug addiction, and gambling addiction. Metabolic disorders such as diabetes may also affect delay discounting, so that people with diabetes might fail to eat properly and exercise, because these tend to benefit the person in the future more than in the present. The findings of the present study fortify the idea that future discounting varies adaptively as a function of multiple levels of life-history and daily adjustments and suggest that it may be more dynamic than has been assumed.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interests with respect to their authorship and/or the publication of this article.

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Supplemental Material

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