A Meta-Analysis of Blood Glucose Effects on Human Decision Making

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The academic and public interest in blood glucose and its relationship to decision making has been increasing over the last decade. To investigate and evaluate competing theories about this relationship, we conducted a psychometric meta-analysis on the effect of blood glucose on decision making. We identified 42 studies relating to 4 dimensions of decision making: willingness to pay, willingness to work, time discounting, and decision style. We did not find a uniform influence of blood glucose on decision making. Instead, we found that low levels of blood glucose increase the willingness to pay and willingness to work when a situation is food related, but decrease willingness to pay and work in all other situations. Low levels of blood glucose increase the future discount rate for food; that is, decision makers become more impatient, and to a lesser extent increase the future discount rate for money. Low levels of blood glucose also increase the tendency to make more intuitive rather than deliberate decisions. However, this effect was only observed in situations unrelated to food. We conclude that blood glucose has domain-specific effects, influencing decision making differently depending on the relevance of the situation to acquiring food.

Keywords: meta-analysis, blood glucose, decision making, ego depletion, dual systems theory, optimal foraging

The notion that the brain is "like a muscle," getting tired with time and use, dates back hundreds of years. Van den Berg noted that 18th century scientists held such views, equating "the efforts of the spirit with those of the body" (Van den Berg, 1986). Over the last several decades, while naïve proposals about how the mind works have been largely replaced with more sophisticated computational views (Pinker, 1997), the idea that certain mental operations require fuel in the form of blood sugar has enjoyed something of a resurgence. For example, a proposal by Gailliot and colleagues that glucose is the fuel for "self-control" has attracted hundreds of citations (Gailliot et al., 2007) and continues to form the basis for research published in prominent outlets (Bushman, Dewall, Pond, & Hanus, 2014).

Buoyed by this robust scholarly literature, the possible role of glucose in cognitive performance has moved from academic circles into the mainstream media. In March 2014, *Time* magazine, in a piece entitled "How to Make Your Kids Smarter: 10 Steps Backed by Science," told readers that "glucose can have beneficial effects on cognitive performance," mentioning specifically, "sustained attention and working memory processes." Such media coverage provides extra urgency to determining what effects glucose has on cognitive and behavioral processes. From a scholarly

standpoint, this question is of potentially great interest as well given the recent uptick in interest in investigating the putative effects glucose might have on various processes.

In the service of addressing this issue, our goals are twofold. Our first goal is an empirical one, to use the existing scholarly literature to determine what effects glucose has on decision-making tasks. That is, given the controversy in the field, and the existence of a sufficiently large number of studies, it is now possible to estimate the size of the effect of glucose on the tasks that putatively are affected. We meta-analyze the extant research to accomplish this goal.

Our second goal is theoretical. There are multiple models that purport to explain the relationships between glucose and decision making. These models make divergent predictions regarding these relationships. To advance theory development, we evaluate these models in light of our findings. Specifically, we derive predictions from each model regarding the effect of blood glucose on the types of decision making covered in this meta-analysis. Subsequently, we evaluate the accuracy of each model in terms of the number of correct predictions the model makes.

Glucose Effects on Behavior and Cognition

Considerable evidence has gathered suggesting some relationship between the level of glucose in the bloodstream and certain cognitive and behavioral processes. It has, for instance, been shown that low blood glucose levels are associated with increased food cravings (Hill, 2007), diminishing food disgust (Hoefling et al., 2009), and, perhaps least surprisingly, increased hunger (Lemmens, Martens, Kester, & Westerterp-Plantenga, 2011) and food intake (Nederkoorn, Guerrieri, Havermans, Roefs, & Jansen, 2009; Raynor & Epstein, 2003). These feeding behaviors are controlled by orexigenic peptides

released in the hypothalamus, which are responsible for monitoring the level of glucose in the blood stream (Bear, Connors, & Paradiso, 2007). The orexigenic peptides also lead to more subtle effects, such as an attention bias toward food stimuli (Mogg, Bradley, Hyare, & Lee, 1998), enhanced perceptual processing of food stimuli (Radel & Clément-Guillotin, 2012), biased size estimation of food stimuli (McClelland & Atkinson, 1948), and intrusive thoughts and associations regarding food (Berry, Andrade, & May, 2007). These perceptual effects seem intuitive from a biological standpoint, functioning to increase foraging and other food- and eating-related behaviors. However, a second group of findings on the effects of blood glucose are considerably less intuitive. It has, for instance, been demonstrated that greater levels of peripheral blood glucose enhance cognitive performance in various ways including the following: working memory, long-term memory, attention and vigilance, reaction times (RTs), verbal fluency, reasoning, and inhibitory control (for reviews, see Dye & Blundell, 2002; Dye, Lluch, & Blundell, 2000; Hoyland, Lawton, & Dye, 2008; Gibson & Green, 2002; Lieberman, 2003; Messier, 2004; Riby, 2004; Smith, Riby, Eekelen, & Foster, 2011). The findings on glucose enhancement are mixed, and there is no strong consensus on how to interpret these effects.

Rather than investigate all of these effects, we focus on decision making because this area still lacks a systematic review and because some important theories that have made it into the bestseller lists (Kahneman, 2011), self-help literature (Baumeister & Tierney, 2011), and even the White House (Lewis, 2012) stem from and make predictions in this area. Here we perform a meta-analysis of research on the effect of glucose on decision making, grouping studies into four classes: *willingness to pay*, *willingness to work*, *time discounting*, and *decision style*.

First, the studies on willingness to pay ask whether subjects are willing to spend more money when their blood glucose is lower; measurements of willingness to pay vary, ranging from, for instance, the amount of money spent on food while shopping (Dodd, Stalling, & Bedell, 1977) to elicitation techniques, such as auctions (Briz, Drichoutis, Nayga, & House, 2013). Similarly, the studies on willingness to work investigate whether people are willing to expend more effort on a task depending on glucose. A typical study along these lines measures how long subjects persist on a puzzle given high or low levels of glucose (Dvorak & Simons, 2009). Third, some studies investigate whether people are more impatient—preferring a smaller reward sooner over a larger reward later—as a function of glucose. As in the prior two cases, tools used to investigate impatience—or an individual's discount rate—rely on either explicit choices, such as subjects choosing between two hypothetical rewards (Wang & Dvorak, 2010) or more indirect methods relying on revealed preferences (Forzano & Chelonis, 2010; Kirk & Logue, 1997; Kuhn, Kuhn, & Villeval, 2014; Logue & King, 1991; Reuben, Sapienza, & Zingales, 2010). Fourth and finally, work on "decision style" investigates whether people are more "intuitive" as opposed to "deliberate" in their decision making when glucose levels are low. Additional detail on each of these categories of tasks is presented in the *Method* section.

Theories of Glucose Effects

There have been many attempts to explain the effects of blood glucose on cognition and behavior, but two classes of explanations have emerged: one that can be thought of very roughly as *constraint models*, largely coming from the psychological literature; and *signal models*, largely coming from economics and biology. For example, a particularly prominent version of the former type of model is the idea that low levels of blood glucose create an energy shortage in higher areas of the brain leading to impaired decision making, working memory, and attention (Gailliot et al., 2007; Messier, 2004). The other group of theories see blood glucose not (only) as an energy source but also as a messenger molecule triggering the release of, for instance, orexigenic peptides that strengthen foraging behaviors. The idea behind these theories is that low levels of blood glucose serve as a cue to the organism that it must allocate more resources to foraging and feeding behaviors. In this view, cognitive processes and behaviors associated with feeding and foraging should be enhanced at the expense of other processes and behaviors, which in turn should be suppressed.

In the following sections, we describe four theories, two of which are examples of the constraint view—*ego depletion* (Gailliot et al., 2007) and *dual systems theory* (Kahneman, 2011)—and two of which are exemplars of the signal view—*optimal foraging theory* (Kacelnik & Bateson, 1997) and the theory of *visceral influences* (Loewenstein, 1996). A key difference between the two types of models is how they treat food as opposed to other sorts of rewards. The two signal theories draw a distinction between food and nonfood. Optimal foraging theory, for instance, is a theory about trade-offs specifically about acquiring food when calories are more urgently needed. The theory does not, in contrast, predict that a hungry organism should be willing to endure greater costs or efforts to obtain nonfood rewards. In contrast, ego depletion, for instance, is specifically proposed as a general phenomenon, positing that people will exert less willpower, in a very general way, across tasks. A virtue of the theory is supposed to be its general effects, entailing that the model draws no distinction between food-related and nonfood-related tasks. So, because the two signal view theories draw a distinction between food- and nonfood-related dependent variables, we discuss the predictions of all four theories with respect to the food/nonfood moderator variable. See Table 1 for an overview of these predictions.

Ego Depletion

Perhaps the most prominent proposal regarding the role of glucose derives from a larger proposal on "self-control" or willpower (for recent reviews, see Carter & McCullough, 2014; Hagger, Wood, Stiff, & Chatzisarantis, 2010). According to this view, the ability to successfully accomplish acts of self-control draws on a resource, which is depleted with use (Baumeister, Vohs, & Tice, 2007; Muraven & Baumeister, 2000; Schmeichel & Baumeister, 2004; Vohs et al., 2008). Gailliot et al. (2007) proposed that the resource in question was glucose. This "resource model" posits a direct relationship between the amount of glucose in the blood stream and willpower, suggesting that in order to execute any act that requires willpower, the brain consumes glucose and, in doing so, slowly depletes itself of this resource leading to a state of ego depletion, or loss of willpower. That is, the resource model proposes that performing certain tasks reduces glucose levels (as an

Table 1
Predicted and Observed Effect Directions

	Results	Ego depletion/ dual systems	Visceral influences	Optimal foraging
Willingness to pay				
Food	—	—	—	—
Nonfood	+	—	+	+
Willingness to work				
Food	—	+	—	—
Nonfood	+	+	+	+
Time discounting				
Food	—	—	—	n/a
Nonfood	—	—	+	n/a
Decision style				
Food	n/a	+	+	n/a
Nonfood	+	+	+	n/a

Note. n/a = not applicable.
+ indicates a positive effect direction with higher blood glucose levels increasing the dependent variable.

absolute matter and more than other tasks reduce glucose) and that performance on subsequent tasks is impaired in virtue of the marginally greater glucose consumption.

This idea is backed by evidence (see especially Gailliot et al., 2007) purporting to show that exerting self-control lowers blood glucose levels, that lower blood glucose levels are associated with poor self-control, and, finally, that administrating glucose counteracts the depletion effect. This proposal and the data that support it have, however, been the subject of considerable scholarly debate (Beedie & Lane, 2012; Kurzban, 2010). Holding aside worries about the details of the analyses of the central paper that invigorated this research area (Kurzban, 2010; Schimmack, 2012), as well as failures to replicate the basic effects (Lange & Eggert, 2014), there are conceptual problems with the model. While certain processes (e.g., vision) might increase glucose consumption, the literature on brain metabolism implies that, outside of such processes, glucose uptake is largely constant across tasks (Gibson, 2007; Lennie, 2003). Indeed, brain imaging data suggest that energy consumption differs very little in brain regions, perhaps by as little as 1% (Raichle & Mintun, 2006).

The ego depletion account is also undermined by additional recent findings. For example, swishing a glucose solution around in the oral cavity yields improvement on certain tasks (Carter & McCullough, 2014; Hagger & Chatzisarantis, 2013; Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012; but see Lange & Eggert, 2014), suggesting that the effect of consuming glucose might have to do with the sensory information as opposed to a role as "fuel" for willpower. Furthermore, Job, Walton, Bernecker, and Dweck (2013) found that the effect that glucose has on performance on a self-control task depends on the subject's beliefs about willpower, a result inconsistent with the notion that a lack of glucose acts as a constraint on performance. Another difficulty for the glucose as fuel for self-control view is that exercise, which consumes glucose, has been found to improve performance on some tasks (Hillman et al., 2009; Temporowski, 2003).

A related model similarly proposes that glucose is required for self-control, but that glucose is rarely if ever unavailable in sufficient quantities to allow for self-controlled behavior (Beedie & Lane, 2012). According to this view, people choose to allocate the

scarce resource, glucose, or not, depending on the priority that they assign to the self-control task at hand. As the authors put it, the "resource is allocated only when necessary, and that necessity is determined by responses to the environment in relation to personal priorities" (p. 149). This implies that performance should depend on these priorities, rather than the current state of glucose or its recent depletion. For this reason, because in the studies analyzed here such priorities are not measured, the model cannot be tested given the data that we have. Therefore, we consider this subspecies of the ego depletion model no further, but look forward to studies specifically aimed at testing predictions of the model. As the authors indicate: "To test this model, the issue of how personally relevant or meaningful an experimental task is—or is not—to a group of experimental participants should be considered" (p. 150).

The basic form of the resource model of self-control (Gailliot & Baumeister, 2007) makes a number of predictions (Kurzban, 2010). In particular, the key prediction of the ego depletion account for the present purpose is that *people with greater levels of blood glucose should perform better on* any *task (including those unrelated to food) requiring self-control than those with lower levels of glucose*. We map this broad prediction onto the narrow set of dependent measures we investigate.

Willingness to Pay

Because ego depletion takes glucose to be the locus of self-control, to the extent that spending less (saving) requires self-control, we take the model to predict that low glucose should be associated with *less* saving (and more spending) whether the domain is food related or not (Baumeister, Vohs, & Tice, 2007; Vohs & Faber, 2007). For instance, Vohs and Faber (2007) proposed that "the factors that lead to the depletion of self-regulatory resources may help to explain when and why specific episodes of impulse buying will occur" (p. 538). Similarly, Gailliot and Baumeister suggest that "[s]elf-control allows people to . . . limit their spending."

Willingness to Work

As in the case of willingness to pay, the prediction of the ego depletion model seems to be clear. Because exerting effort requires willpower—and because willpower depends on glucose levels—glucose levels should be positively related to effort expended. For instance, Gailliot et al. (2007) explicitly proposed that glucose levels would (positively) predict persistence on a frustrating (impossible) task. More generally, Gailliot and Baumeister (2007) suggested that "high effort involved in rational, intelligent decision making may deplete the same resource needed for self-control . . ." (p. 304). As discussed earlier, this exertion of willpower should not depend on whether the task in question is food related or not. Therefore, the prediction is for an effect of glucose on effort in both cases, with lower glucose being associated with lower willingness to work.

Time Discounting

In parallel with our claim regarding willingness to work, we take it as uncontroversial that the ego depletion framework predicts that being more patient—with respect to either money or food—

requires exerting more self-control. As Muraven and Baumeister (2000) put it: "People exert self-control when they follow rules or inhibit immediate desires to delay gratification" (p. 247). Given the relationship posited between self-control and glucose, we assume that the ego depletion view predicts an effect of glucose for both food-related and nonfood-related discounting tasks. That is, lower glucose levels should result in a decreased ability to put off consumption of rewards in any form sooner in favor of larger rewards later. Indeed, self-control in some parts of the literature is glossed in these terms, as the "ability to resist immediate pleasures in favor of longer-term goals" (Kool, McGuire, Wang, & Botvinick, 2013).

Decision Style

Finally, we think that the ego depletion view predicts an effect of low glucose on decision style for both food-related and nonfood-related tasks. Because the resource model takes glucose to be related to the use of executive function and working memory, the implication is that less glucose should lead to less deliberative reasoning, independent of the domain in question. Indeed, Masicampo and Baumeister (2008) write: "we tested the hypothesis that more blood glucose (which serves as fuel for the brain) is needed for the effortful, rule-based [deliberate] process than for the less effortful [heuristic] process, so that the former type of decision making is impaired when glucose has been depleted by prior, even irrelevant, activities" (p. 255).

Dual Systems Theory

Dual systems theories cover a wide range of models sharing the notion that the mind consists of two systems competing for control over cognition and behavior. One of these systems (System 1) is fast, unconscious, intuitive, low effort, with a large processing capacity, and the second system (System 2) is slow, conscious, deliberate, high effort, with a limited processing capacity. (For a recent thorough review, see Kahneman, 2011.)

Models that posit that behavior is determined by multiple systems have a long history, which Strack and Deutsch (2004) date at least as far back as Freud (1933/1949). The proposal that there are two fundamental kinds of systems has a number of incarnations, in the literature in cognitive psychology generally (Evans, 2008; Sloman, 1996; Schneider & Shiffrin, 1977; Stanovich, 1999), as well as in economics (Thaler & Shefrin, 1981), social psychology (Chaiken, Liberman, & Eagly, 1989; Kruglanski & Orehek, 2007), and, in particular, in the literature on the delay of gratification (Metcalfe & Mischel, 1999). Indeed, Hoffmann, Friese, and Strack (2009) proposed that "most instances of temptation can be described as a tug-of-war or conflict between impulses on one hand and self-control on the other."

System 1, the fast, intuitive "impulsive" system, will tend to lead to choosing to be lazy rather than diligent, impatient for a reward rather than patient, and, of course, impulsive. To the extent that System 2 is influencing behavior, decisions should have the reverse quality. The dual systems perspective implies that lower levels of glucose will lead to more System 1 reasoning and behavior (van den Bos & McClure, 2013). Dickinson, McElroy, and Stroh (2013), for instance, rely explicitly on this idea: "In the context of a dual systems framework of brain function [. . .] glucose supplementation shifts the relative weight of decision

making away from the more automatic System 1 in favor of the more deliberative System 2." A related but distinct view is that of van den Bos and McClure (2013), who suggest that for an organism that is hungry (i.e., low blood glucose), "a cue that predicts future reward such as the promise of money and a temporal delay, we would expect that the valuation system is enhanced relative to control (nonhungry) conditions" (p. 67). Low levels of blood glucose, then, activate the reward system rather than inhibit the control system, enhancing System 1 relative to System 2. That is, assuming that low levels of blood glucose shift the balance from System 2 to System 1, it follows that *decision makers with low levels of blood glucose will become more impulsive, less likely to persist on effortful tasks, and more likely to make intuitive rather than deliberate decisions.*

Willingness to Pay

Insofar as automatic System 1 processes are activated in the context of making decisions regarding conserving money for both the food and nonfood domains of decision making, the dual systems view seems to predict a main effect of glucose but, crucially, does not seem to predict moderation regarding food versus nonfood-related tasks. Note that if one were to argue that the dual systems framework *does* predict such moderation, then a similar argument should be applied uniformly across the four types of tasks. That is, either dual systems models should be taken to predict no moderation across all four classes of tasks, or it should be taken to predict moderation across all of them. We believe the most natural prediction to assign to the dual systems framework is an effect of glucose with no moderation.

Other Measures

The dual systems framework suggests, for the reasons sketched earlier, that lower levels of glucose should lead to lower willingness to work (Kahneman, 2011), more impulsive decisions, (Fudenberg & Levine, 2006; McClure, Laibson, Loewenstein, & Cohen, 2004; van den Bos & McClure, 2013), and a less deliberate decision style.

Given that dual systems theory makes identical predictions to ego depletion theory and furthermore assumes a similar causal mechanism, we refer to the two theories jointly.

Optimal Foraging Theory

Optimal foraging theory directs attention to the costs and benefits associated with acquiring the calories and nutrients required for life. The main premise of optimal foraging is that animals should allocate their resources dynamically depending on their current energy state; for example, with high or low levels of blood glucose. When energy is low, resources should be shifted toward foraging and away from other tasks such as courtship and reproduction (Abrams, 1993; Kolluru & Grether, 2005). This prediction applies when foraging and nonforaging activities are mutually exclusive; that is, time spent courting precludes foraging and vice versa. Another tradeoff that organisms face is that acquiring food generally entails some costs, often in the form of risks of, for instance, predation, during foraging episodes. This line of reasoning implies that a very hungry organism might be best off enduring

the risks of foraging while a satiated organism, having less immediate need of additional calories, might be best off choosing safety over foraging (Stephens, 1981). This principle is known as the energy-budget rule (Kacelnik & Bateson, 1997). Because low blood glucose signals a negative energy budget, the organism should be more willing to take risks and be more motivated to obtain food rewards sooner rather than later.

These ideas, applied to humans, imply that people's decisions in various domains will depend in a systematic way on their caloric state, as indexed by quantities such as blood glucose. Specifically, *this view implies that people with lower levels of glucose will be more inclined to take food-related risks, be more motivated to obtain food rewards, and be more impatient to obtain food rewards*.

Willingness to Pay and Work

While optimal foraging theory does not make predictions about willingness to pay for food or nonfood items per se, some studies have demonstrated that human decision makers treat monetary resources in accordance with the energy-budget rule, shifting from risk averse to risk seeking under a negative monetary budget (Pietras & Hackenberc, 2001; Pietras, Searcy, Huitema, & Brandt, 2008). Given the similarity between food and monetary resources, we predict that low blood glucose will increase the willingness to pay for food but reduce the willingness to pay for rewards not associated with food. Related, hungry organisms, in virtue of their increasingly urgent need for additional calories, are predicted by this framework to make behavioral tradeoffs toward activities that will differentially lead to the acquisition of food and away from other activities. Hungry organisms, then, should be expected to endure greater costs—including the expenditure of effort and enduring of risks—than less hungry organisms.

Time Discounting and Decision Style

The prediction from optimal foraging theory for these two measures is, we believe, debatable. Our view is that a strict interpretation of the theory, which mostly has to do with foraging for food and taking risks to obtain food, does not make a clear prediction about discounting. To the extent that it does make a prediction, it suggests that hungry people ought to be more impatient. Wang and Dvorak (2010, p. 183), in fact, leaned on this line of argument, writing:

> 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 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.

Note the use of the general term "resources" as opposed to "food" in the exposition of this prediction. We believe that this prediction, however, is only loosely licensed by the theory, and so we chose to be conservative in attributing a prediction, and so leave these cells with the notation "n/a" in Table 1. For similar reasons, we make a similar notation for decision style.

Visceral Influences

Finally, Loewenstein (1996), in a line of reasoning that bears some similarity to the ideas discussed previously in the context of optimal foraging theory, proposed that hunger might cause people to value goods and behaviors differently, in turn altering the goals they choose to pursue. Hunger, he argues, exerts a "visceral influence," making goals relating to eating more desirable, while diminishing the desirability of other (noneating-related) goals.

Willingness to Pay

The visceral influences framework suggests that the effect of an impulse depends on the reason for the visceral arousal. Indeed, Loewenstein writes: "At sufficient levels of intensity, individuals will sacrifice almost any quantity of goods not associated with the visceral factor for even a small amount of the associated good" (Loewenstein, 1996 pp. 272–273). This implies that effects of blood glucose will be specific to the associated good, which in this case would mean whether the good contains calories and can satisfy the need for food. Therefore, this model predicts an increased willingness to pay for food when blood glucose is low, that is, when the need for food is high, and a decrease in willingness to pay for any other good.

Willingness to Work

The visceral influences model highlights the *relative* importance of goals, focusing attention on how present state makes obtaining a particular goal or reward more or less appealing. Hunger, then, by increasing the hedonic value of food rewards, can be thought of as increasing the motive to endure the unpleasantness of effort *relative* to the expected hedonic value of obtaining food rewards (Loewenstein, 1996). For this reason, lower glucose levels (hunger) should lead to greater willingness to work (i.e., endure the unpleasantness of effort) *in the service of obtaining food rewards*.

Time Discounting

Loewenstein made the prediction regarding discounting explicit, writing: "A hungry person, for example, is likely to make short-sighted tradeoffs between immediate and delayed food" (p. 275). This suggests that low blood glucose should increase time discounting for food but not for other goods; indeed, Loewenstein also writes that "this present-orientation, however, applies only to goods that are associated with the visceral factor [. . .] A hungry person would probably make the same choices as a non-hungry person between immediate and delayed money (assuming that food cannot be purchased) or immediate and delayed sex" (p. 275). In other words, if we assume that food can, in fact, be easily purchased with money, then low blood glucose might increase time discounting both for food and for money. The specific predictions of the visceral influences view therefore depend on the interpretation of whether money can substitute food. We believe that the most coherent prediction is that low blood glucose should decrease time discounting for money.

Decision Style

The prediction regarding decision style is somewhat less clear. Loewenstein writes: "Although visceral factors should be and are

taken into account in decision making, they also influence behavior more directly. Hunger, thirst, sexual desire, pain, and indeed virtually all visceral factors, can influence behavior without conscious cognitive mediation" (p. 275). Later Loewenstein suggests that: ". . . there are certain types of influences or incentives that operate independently of, and overwhelm, individual deliberation and volition" (p. 276). We consider this to be a prediction that low blood glucose should lead to more intuitive rather than deliberate decision making, especially when this would be beneficial to obtaining food. If deliberation, on the other hand, is necessary to obtain food, it is less certain whether low blood glucose would lead to more intuitive decision making. When no food is involved in the task, we assume that decision makers will always be less deliberate because the goal to obtain food crowds out all other goals.

Summary of Models

We test the predictions of the models using a meta-analytic analysis of published results of studies that investigate the four types of tasks discussed previously with participants with high or low levels of glucose. Crucially, given our understanding of the predictions of the models, we include a single moderator variable: whether the dependent measure is related to food or not. For instance, as we have just seen, the visceral influences view and the optimal foraging view predict that individuals who are low on blood sugar will be willing to pay more for food, but not for nonfood items. Because the models make similar predictions for some tasks—for example, all models make the intuitive prediction that people with low glucose will be more willing to pay for food and adopt a heuristic decision style—the results contrasting food and nonfood tasks is especially critical.

In sum, the ego depletion and the dual systems model, because they are proposed to be general in their applicability, do not predict a difference for food-related and nonfood-related tasks. They predict that those with low levels of glucose will show, generally, greater willingness to pay, less willingness to work, greater time discounting, and greater reliance on heuristic decision making. The visceral influences view, as well as the optimal foraging view, predicts that willingness to pay and work for nonfood items will, in contrast, decrease for those with lower levels of glucose. The predictions for discounting and decision style are unclear for optimal foraging theory. Finally, the visceral influences view makes the (debatable) prediction that under low blood glucose time discounting for food will be stronger, but not for nonfood items.

Method

Literature Search Procedure

Thirty-six published and unpublished articles were included in the meta-analysis. The articles were initially searched through databases. The search was executed twice: First, a pilot search was conducted to generate keywords and databases and, second, a main search was conducted in which appropriate studies were identified. No limitations on publication date were imposed. The searched databases included ISI Web of Science and PsychInfo. Grey literature was searched through Google Scholar, which indexes journals not included in ISI, conference and workshop proceedings,

research and technical reports, theses, books and book chapters, as well as university websites (Kousha & Thelwall, 2008; Shultz, 2007).

The keywords included combinations of the following terms: "blood glucose," hunger, "food deprivation" AND "decision making," choice, judgment, motivation, "goal pursuit," "goal striving," goals, effort, "impulse control," "self-control," "self-regulation," willpower, "delay of gratification," temptation, "ego depletion," "self-depletion," "ego strength," aggression, volition, "working memory," cooperation. After the second database search, reference lists of included papers were searched. Additional studies were identified through contact with authors. The last search was carried out in March 2014.

The meta-analysis included experimental or quasi-experimental studies on humans in which the independent variable manipulated or measured blood glucose, or in other ways operationalized blood glucose, such as through measurement of hunger, food intake, or controlling food deprivation. An additional requirement was that the dependent variable measured decision making or action selection behaviors. Studies measuring cognitive performance, emotions, or behaviors not related to decision making were not included. Studies in which participants were selected based on a clinical diagnosis, psychographic, or specific sociodemographic traits (e.g., eating disorders, diabetic symptoms, clinically obese, smokers, or drug addicts) were excluded because these subgroups are likely to respond differently to fluctuations in blood glucose.

Inclusion Criteria

The search process yielded 192 full text records that were screened for eligibility. Study eligibility was established using the following inclusion criteria:

(1) The independent variable operationalized blood glucose, either through glucose administration, glucose measurement, cephalic phase reaction, food deprivation, or via a hunger score. Studies on any other need state, such as sleep deprivation, oxygen deprivation, or fluid deprivation, were excluded from analyses as were studies based on diabetic symptoms and glucose tolerance tests ($k = 16$).

(2) The dependent variable was related to decision making or action selection. Studies of general cognition, such as long-term or short-term memory, ($k = 47$), perception and attention ($k = 32$), emotion and aggression ($k = 19$), eating behavior ($k = 15$), neuroscience ($k = 9$), and exercise ($k = 4$) were excluded.

(3) To be included in the qualitative synthesis, a minimum of two studies had to be available on a given topic. Single studies on isolated topics ($k = 8$) such as variety seeking, social preferences, judgments of female attractiveness, weight loss planning, and choice of healthy and unhealthy foods were excluded. Studies operationalizing but not analyzing the relationship between blood glucose and decision making were also excluded ($k = 4$). Studies reporting effect sizes as not significant or as $p > .05$ or $p > .10$ were included in the analysis by imputation ($k = 2$).

(4) To be included in the quantitative synthesis, a minimum of four effect sizes had to be available on a given topic. For this reason, studies on decision making under risk ($k = 2$) were excluded from further analyses.

Eventually, 36 studies met all inclusion criteria for the quantitative synthesis. A diagram of the flow of documents is shown in Figure 1.

Coding Procedure

The included studies were coded with respect to the independent variable, dependent variable, and moderator variable. The coding was first done by the first author. To establish the reliability of the coding procedure, an independent coder blind to the study hypotheses then coded all included studies. The independent coder was not informed about which effect sizes had been extracted from the included studies. The two coders had a high level of agreement for all three variables, $\kappa_{iv} = .80$, $\kappa_{dv} = .74$, and $\kappa_{mv} = 1.0$. Only the coding of the first author was used in subsequent analyses.

Independent variables were divided into five classes: studies in which blood glucose was directly manipulated by having a treatment group consume either food or sugar rich beverages (*glucose administration*), studies in which blood glucose was measured (*glucose measurement*), studies in which blood glucose was manipulated by having a treatment group fast before the study either by direct instruction from the experimenter or by exploiting time of day variation in food intake, for example, before and after lunch (*food deprivation*), studies in which blood glucose was manipulated by inducing a cephalic phase reaction (Mattes, 1997) by, for instance, exposing hungry participants to food smells or symbolic amounts of food (*cephalic phase*), and, finally, studies in which hunger was measured using visual analogue or Likert scales (*hunger score*).

As described previously, the dependent variables were grouped into four classes of studies: *willingness to pay*, *willingness to work*, *time discounting*, and *decision style*. The studies of willingness to pay used different preference elicitation techniques based on stated and revealed preferences. The stated preference studies included tasks such as rating of purchase intentions (Brendl, Markman, & Messner, 2003; Tom & Rucker, 1975), while the revealed preference studies included tasks such as money spent on food during a shopping trip (Dodd et al., 1977; Gilbert, Gill, & Wilson, 2002; Mela, Aaron, & Gatenby, 1996; Nisbett & Kanouse, 1969; Steinberg & Yalch, 1978), amount of food or calories purchased during shopping trip (Beneke & Davis, 1985; Nederkoorn et al., 2009; Tom, 1983), money donated to charity (Briers, Pandelaere, Dewitte, & Warlop, 2006), money donated to an experimental partner (Aarøe & Petersen, 2013; Briers et al., 2006; Petersen, Aarøe, Jenson, & Curry, 2014), and willingness to pay for food elicited by a fourth price Vickrey auction (Briz et al., 2013).

The studies of willingness to work similarly used stated and revealed methods for assessing participants' willingness to invest effort in a given task. Stated preference methods included tasks such as hypothetical willingness to help a stranger (Dewall, Baumeister, Gailliot, & Maner, 2008; Gailliot et al., 2007), while revealed preference methods included tasks such as effort spent to obtain food on a computerized progressive ratio schedule task (Bulik & Brinded, 1994; Epstein, Truesdale, Wojcik, Paluch, & Raynor, 2003; Nasser, Evans, Geliebter, Pi-Sunyer, & Foltin, 2008; Raynor & Epstein, 2003; Saelens & Epstein, 1996), persistence on a puzzle or anagram task (Dvorak & Simons, 2009; Geeraert & Yzerbyt, 2007), and persistence on an unsolvable figure tracing task (Gailliot et al., 2007).

Studies of time discounting were also divided between stated and revealed preference studies, with the stated preference studies including tasks such as hypothetical choice between sooner-smaller and later-larger rewards (Hoefling & Strack, 2010; Li, 2008; Rasmussen, Lawyer, & Reilly, 2010; Wang & Dvorak, 2010), and the revealed preference studies included incentive compatible choice between sooner-smaller and later-larger re-
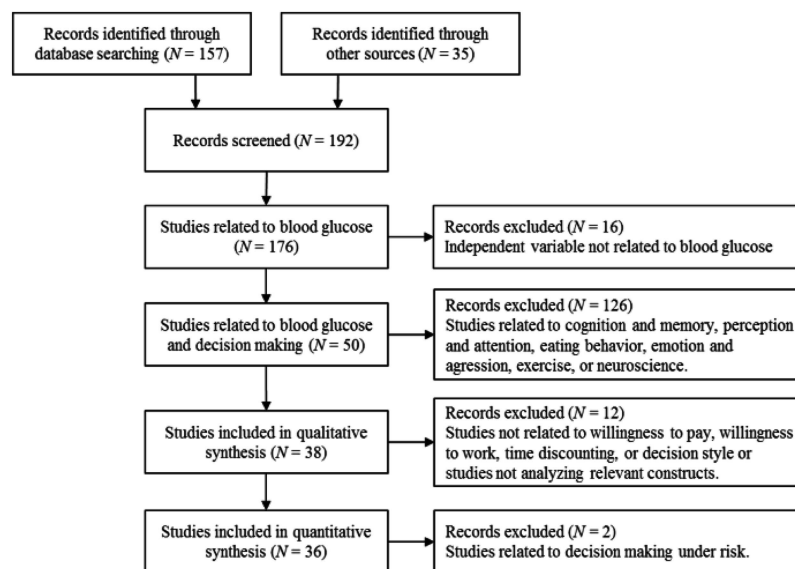

Figure 1. Flow of documents. One hundred ninety-two full-text records were screened for eligibility.

wards (Forzano & Chelonis, 2010; Kirk & Logue, 1997; Kuhn et al., 2014; Logue & King, 1991).

The smallest group of studies was on decision style. The five studies each used a different measure of the tendency to make deliberate rather than intuitive or automatic judgments or choices. The studies included tasks such as choice accuracy for car and job options during deliberate versus intuitive decision making (M. W. Bos, Dijksterhuis, & van Baaren, 2012), granting parole to prisoners versus rejecting parole with rejection being the default choice (Danziger, Levav, & Avnaim-Pesso, 2011), susceptibility to attraction bias during apartment choice (Masicampo & Baumeister, 2008), tendency to choose an unlikely option during a probability learning task as an indicator of deliberation (McMahon & Scheel, 2010), and, finally, Bayes switching task as a measure of Bayesian versus heuristic decision making (Dickinson, McElroy, & Stroh, 2013).

The moderator variable was grouped into two classes: If the experimental task was incentivized with food or other caloric rewards, or if the evaluative dimension was food related, the study was coded as *food related*; in all other cases, the study was coded as *not food related*.

Statistical Approach

Construct Validity of the Independent Variable

One of the concerns of the current analysis is that the included studies rely on different operationalizations of blood glucose: blood glucose measurement, glucose administration, cephalic phase reaction, hunger score, and food deprivation. These five operationalizations may differ with respect to their construct validity; that is, not all operationalizations are necessarily equally good measures of the true level of blood glucose. If the five operationalizations differ in construct validity this could introduce a bias in the meta-analysis because studies with higher construct validity tend to yield higher effect sizes. Studies with lower construct validity on the other hand yield smaller effect sizes because study artifacts such as measurement reliability or construct validity attenuate effect sizes (Hunter & Schmidt, 2004). To see whether there were meaningful differences in construct validity and potentially correct for this, we reviewed the identified studies for reported measurement reliabilities. Only one study reported the reliability of their blood glucose measurement, $r_{xx} = .97$ (Dvorak & Simons, 2009). To estimate the reliability of the remaining studies, we surveyed literature on the reliability of hand-held blood glucose measurement devices, such as those used in the included studies and literature on the relationship between blood glucose and cephalic phase reactions, food deprivation, and hunger. Besides Dvorak and Simons (2009), we identified five other studies in which the reliability of hand-held blood glucose measurement devices was reported (Critchell et al., 2007; Hoedemaekers, Klein Gunnewiek, Prinsen, Willems, & Van der Hoeven, 2008; Kanji et al., 2005; Maser, Butler, & DeCherney, 1994; Vlasselaers et al., 2008). The average reliability from the six studies of hand-held blood glucose devices was $r_{xx} = .95$. Two studies were identified on the relationship between cephalic phase reaction and blood glucose (Bruce & Storlien, 2010; Ott et al., 2011). The average reliability was $r_{xx} = .67$. Four studies were identified on the relation between hunger and blood glucose (Anderson, Catherine,

Woodend, & Wolever, 2002; Ciampolini & Bianchi, 2006; Flint et al., 2007; Lemmens et al., 2011) and of these, two studies reported two reliabilities. Averaging the six reliabilities yielded $r_{xx} = .403$. Three studies were identified on the relationship between blood glucose and food deprivation (Green, Elliman, & Rogers, 1997; Owen, Scholey, Finnegan, Hu, & Sünram-Lea, 2012; Sünram-Lea, Foster, Durlach, & Perez, 2001); that is, a variable period of food deprivation, and averaging yielded a reliability of $r_{xx} = .503$. For the last group of studies in which blood glucose was manipulated by administrating sugar or food to the study participants, we assumed perfect construct validity based on the fact that these studies relied on a random assignment to a direct manipulation of glucose levels. Note, however, that this does not necessarily imply that participants within a condition have the same absolute levels of blood glucose.

According to psychometric meta-analysis, imperfect construct validity of study i attenuates the observed effect size r relative to the true effect size ρ proportional to the square root of the reliability r_{xx}:

$$r = \rho\sqrt{r_{xx}}$$

The square root of the reliability r_{xx} is referred to as the artifact multiplier a_i and is a more direct way of seeing the expected attenuation. Studies in which blood glucose, for instance, is operationalized via food deprivation have an average reliability of $r_{xx} = .50$. The artifact multiplier a_i is thus $\sqrt{.50} = .71$, which means that food deprivation studies on average result in effect size estimates that are 71% of the true effect size ρ; that is, the effect size which would be obtained using an operationalization with perfect construct validity such as glucose administration.

To inspect the influence of construct validity on the meta-analysis, we conducted a moderator analysis for each independent variable subgroup. To this end, we coded all studies in a positive effect direction and conducted a meta-analysis on the observed correlations for each subgroup using the Hunter and Schmidt approach (Hunter & Schmidt, 2004). Despite the noise introduced by aggregating across levels of the dependent and moderator variables, the results suggest that studies with lower levels of construct validity on average yield lower effect sizes. Table 2 shows the artifact multipliers for each independent variable subgroup and the observed average effect sizes. We take these results to indicate that the five operationalizations of the independent variable map onto the same physiological construct (blood glucose) although with varying levels of construct validity. To minimize the bias introduced by this artifact we conducted the follow-

Table 2

Moderator Analysis of the Independent Variable Showing the Number of Studies (k), Artifact Multiplier (A), Average Effect Size of the Attenuated (r), and Unattenuated (rᵘ) Subgroups

Independent variable subgroup	k	A	r	r^u
Glucose administration	17	1.00	.25	.25
Blood glucose measurement	6	.96	.28	.28
Cephalic phase manipulation	4	.67	.17	.20
Food deprivation	12	.50	.18	.25
Hunger score	3	.40	.06	.10

ing meta-analysis using a psychometric approach as recommended by Hunter and Schmidt.

Computation of Effect Sizes

Effect sizes were computed as the Pearson's correlation coefficient r using the effect size determination program available in *Comprehensive Meta-Analysis*. Wherever possible, effect sizes were computed directly from means and standard deviations, F tests, t tests, or p values. For studies reporting correlation values, no further transformations were performed. Whenever studies reported threshold p values, priority was given to means, F values, or t-values. When no other information was available the p value was conservatively set to the upper bound, for example, a study reporting $p < .05$ was coded as $p = .05$ (Cooper, Hedges, & Valentine, 2009).

Effect sizes were computed by the first author and an independent expert; differences were resolved by discussion. When a study reported effect sizes for several conceptually similar dependent variables, the effect size most similar to that of other studies was extracted. Two studies reported effect sizes for both the food and nonfood subgroups (Brendl et al., 2003; Rasmussen et al., 2010) and one study (Briz et al., 2013) reported effect sizes for both willingness to pay and time discounting. Studies reporting effect sizes for independent subgroups (for instance men and women) were collapsed. Effect sizes were coded so that a positive effect direction indicates that higher blood glucose led to a higher willingness to pay, a higher willingness to work, a higher time discounting rate, and a higher propensity to make deliberate rather than automatic decisions.

Two studies reported effect sizes as "not significant"; that is, $p > .05$ and $p > .10$ (Mela et al., 1996; Rasmussen et al., 2010). In both cases, the effect size was imputed as the expected effect size correlation for that particular subgroup and blood glucose operationalization (Cooper et al., 2009). For instance, Mela and colleagues (1996) reported a nonsignificant effect ($p > .10$) of food deprivation on willingness to pay for food ($N = 96$). With an average effect size for willingness to pay for food of $\rho = -.17$ and an attenuation of 71% due the use of food deprivation as independent variable, this yields an expected effect size $r = -.12$, $p = .242$. Rasmussen and colleagues (2010) reported two effect sizes as not significant ($p > .05$) for time discounting of food and nonfood ($N = 53$). Following the previous method, the imputed effect sizes were $r = .25$, $p = .07$ and $r = .13$, $p = .36$, respectively. In both cases, the expected significance level is above the reported alpha level.

Effect Size Averaging

In light of the previous analysis indicating a potential bias stemming from varying levels of construct validity in the independent variable, we conducted a psychometric meta-analysis following the Hunter and Schmidt approach (Cooper et al., 2009; Hunter & Schmidt, 2004). The analysis computes the true average effect size ρ based on the unattenuated correlation coefficients r_i^u, the sample size n_i, and the artifact multiplier a_i:

$$\rho = \frac{\sum_{i=1}^{k}(n_i a_i^2 r_i^u)}{\sum_{i=1}^{k}(n_i a_i^2)}$$

In addition to the average effect size, ρ, we report the average effect size of the attenuated correlations $\bar{r}$, and the 95% credibility interval CV_{95} of ρ. The CV_{95} is different from the confidence interval CI_{95} in that it is based on the SD_ρ instead of the SE_ρ. Whereas the CI_{95} indicates the degree of error in the estimate of ρ because of sampling error, the interpretation of the CV_{95} is that 95% of the values in the ρ distribution lie in this interval (Hunter & Schmidt, 2004). To estimate the amount of heterogeneity in effect sizes, we computed a metric with a similar interpretation to I^2, which we refer to here as the pseudo-I^2 (Borenstein, Hedges, Higgins, & Rothstein, 2011). The pseudo-I^2 is the percentage of unexplained variance after correcting for sampling error and artifacts; that is, the between studies variance component for the unattenuated effect size parameters $(T^u)^2$ divided by the weighted variance of the unattenuated correlations $(S^u)^2$:

$$\text{pseudo} - I^2 = (T^u)^2/(S^u)^2$$

where $(S^u)^2$ is the weighted variance of the unattenuated correlations:

$$(S^u)^2 = \frac{\sum_{i=1}^{k} n_i a_i^2 (r_i^u - \bar{r}^u)^2}{\sum_{i=1}^{k} n_i a_i^2}$$

and $(T^u)^2$ is the between studies variance component for the unattenuated effect size parameters:

$$(T^u)^2 = (S^u)^2 - \frac{\sum_{i=1}^{k} n_i a_i^2 V_i^u}{\sum_{i=1}^{k} n_i a_i^2}$$

The moderator analysis was based on a hierarchical breakdown strategy (Hunter & Schmidt, 2004). Support for moderation was observed by a reduction in the pseudo-I^2 and a change in the average corrected effect size estimates for the subgroups relative to the global group. A moderator was considered statistically significant given no overlap in the CI_{95} and practical significance was assessed through the degree of overlap in the CV_{95}.

Results

The main analysis followed a hierarchical breakdown strategy beginning with an analysis of all included studies and then breaking down first by the dependent variable and then by the moderator variable. The results are presented in Table 3, with the main variables of interest being the corrected effect size estimate, ρ, and the heterogeneity, pseudo-I^2. Estimates of the average uncorrected effect sizes, r, and their standard deviations, SD_r, present the results of a bare-bones analysis; that is, ignoring differences in construct validity between individual studies. Table 4 contains an overview of all included studies.

The analysis of all included studies revealed close to zero effect of blood glucose, $\rho = -.04$, and a high degree of heterogeneity, pseudo-$I^2 = 78\%$. Breaking down by dependent variable strongly reduced the degree of heterogeneity for time discounting, pseudo-$I^2 = 21\%$, and decision style, pseudo-$I^2 = 0\%$, but not for willingness to pay or willingness to work. For all but one dependent variable, the corrected effect size estimates were significantly different from the global estimate. Breaking further down by moderator variable reduced the degree of heterogeneity to zero for all subgroups except willing-

Table 3
Main Results on the Effect of Blood Glucose on Decision Making

Group	k	N	r	SD_r	ρ	SD_ρ	CV_{95} LL	CV_{95} UL	CI_{95} LL	CI_{95} UL	Pseudo-I^2
All studies	42	3994	−.04	.21	−.04	.24	−.51	.44	−.07	.00	78%
Willingness to pay	15	2535	−.07	.14	−.09	.18	−.44	.25	−.16	−.03	75%
Food	11	2273	−.12	.08	−.17	.10	−.36	.02	−.26	−.07	52%
Nonfood	5	411	.22	.00	.24	.00	.24	.24	.10	.39	0%
Willingness to work	12	444	.17	.33	.18	.30	−.40	.77	.09	.28	76%
Food	5	91	−.47	.10	−.50	.00	−.50	−.50	−.65	−.36	0%
Nonfood	7	353	.33	.07	.34	.00	.34	.34	.22	.46	0%
Time discounting	10	707	−.21	.10	−.25	.07	−.39	−.11	−.33	−.17	21%
Food	6	408	−.24	.10	−.35	.00	−.35	−.35	−.22	−.48	0%
Nonfood	5	352	−.17	.07	−.18	.00	−.18	−.18	−.03	−.32	0%
Decision style	5	308	.27	.10	.26	.00	.26	.26	.12	.41	0%

Note. k = number of studies; N = sample size; r = attenuated effect size; SD_r = standard deviation of the attenuated effect size; ρ = unattenuated effect size; SD_ρ, = standard deviation of the unattenuated effect size; CV_{95} LL = lower limit of the 95% credibility interval; CV_{95} UL = upper limit of the 95% credibility interval; CI_{95} LL = lower limit of the 95% confidence interval; CI_{95} UL = upper limit of the 95% confidence interval; pseudo-I^2 = within-group heterogeneity.

ness to pay for food, pseudo-I^2 = 52%. The large pseudo-I^2 value for this subgroup suggests between-study variability not accounted for by artifacts or sampling error (Higgins & Thompson, 2002). To explore the heterogeneity, we conducted a hold one out analysis. The analysis revealed that one study (Beneke & Davis, 1985) was responsible for all heterogeneity in the subgroup. Excluding this study yielded a slightly higher effect size, ρ = −.22, and a complete reduction in heterogeneity, pseudo-I^2 = 0%. At the lowest subgroup level, effect size estimates were significantly different for the food/nonfood subgroups for willingness to pay and willingness to work. For time discounting, the food/nonfood subgroups resulted in a decrease in the pseudo-I^2 yet overlapping CI_{95} intervals. However, the food/nonfood subgroup CV_{95} intervals did not overlap, which for practical purposes suggests an effective moderator. For decision style, only the nonfood subgroup was observed. Figure 2 shows a forest plot of the unattenuated effect sizes.

Overall, the hierarchical breakdown supports an analysis of the data at the lowest subgroup level. Figure 2 provides a visual intuition for the hierarchical breakdown. One can imagine the global analysis as the black line going through $r = 0$; in fact, the global effect size estimate is not significantly different from zero. A decomposition of the global effect size estimate into dependent variable groups (illustrated as grey diamonds) suggests that the absence of any global effect is actually because of the averaging of two positive and two negative effect size estimates. A further decomposition into food/nonfood subgroups (illustrated as white and black diamonds) shows how the dependent variable estimates result from the averaging of, at least in the case of willingness to pay and willingness to work, extremely different subgroups.

As a robustness check (Appendices A and B) shows the results excluding the three imputed studies and results where the imputed studies have been set to zero effect size ($r = 0$). When computing the average effect size for all studies and the overall effect for willingness to pay and time discounting, the studies providing multiple effect sizes were collapsed into single estimates to maintain the assumption of independence.

Publication Analysis

Before drawing any conclusions from the analysis, it is important to assess the extent of publication bias. Most publication analyses are based on estimates of funnel plot asymmetry that gauge the individual study effect size estimate as a function of study precision. However, these methods are likely compromised if a dataset contains any small-study effect other than publication bias because this is likely to influence the symmetry of the funnel plot, even in the absence of publication bias. In the current dataset, the correlation between the construct validity of the independent variable and the sample size is $r = -.34$, which means that larger studies are generally less construct valid and hence should result in attenuated effect sizes. This means that even in the absence of publication bias, we should expect an asymmetric funnel plot. Given the small number of studies in each subgroup and a known small-study effect, it would therefore be difficult to interpret results from, for instance, Egger's regression (Egger, Smith, Schneider, & Minder, 1997) or by visually inspecting funnel plot asymmetries. More recent publication analyses such as precision-effect test or precision-effect estimate with standard error (for a recent overview, see Carter & McCullough, 2014) would also be compromised by the small number of studies in each subgroup.

Another possibility to infer the likelihood of publication bias is to examine the number of unpublished and significant studies included in the analysis on the theory that significant studies are more likely to get published. The current dataset contained 44 effect sizes, 17 of which did not reach significance at the p = .05 level. Of the 36 included articles, three were unpublished. The three unpublished studies provided four effect sizes, one of which did not reach significance. Although this should be taken with some caution, this pattern does suggest that the unpublished studies are actually more likely to reach significance (25% are nonsignificant, *ns*) compared with the published studies (40% are *ns*), which speaks against publication bias.

As a final robustness check, we conducted a trim-and-fill analysis (Duval & Tweedie, 2000) on each moderator subgroup using the observed (attenuated) correlations to estimate a cor-

Table 4

Overview of Included Studies and Their Sample Size (n^I), Attenuated (r_I) and Unattenuated (r_I^U) Effect Sizes, Artifact Multiplier (a_I), Independent Variable Group (IV), Dependent Variable Group (DV), and Moderator Variable Group (MV)

Authors	n^i	r_i	a_i	r_i^u	IV	DV	MV
Beneke & Davis 1985	596	.03	.63	.05	H	WTP	F
Bos et al. 2012	82	.22	1.00	.22	GA	DS	NF
Brendl et al. 2003 (food)	149	−.10	.82	−.12	C	WTP	F
Brendl et al. 2003 (non-food)	149	.17	.82	.21	C	WTP	NF
Briers et al. 2006 (1)	66	.27	1.00	.27	GA	WTP	NF
Briers et al. 2006 (2)	58	.27	.82	.32	C	WTP	NF
Briz et al. 2013	252	−.13	.71	−.18	FD	WTP	F
Briz et al. 2013	252	−.20	.71	−.28	FD	TD	F
Bulik & Brinded 1994	6	−.29	.63	−.45	FD	WTW	F
Danziger et al. 2011	8	.91	.71	1.00	FD	DS	NF
DeWall et al., 2008 (2)	59	.31	1.00	.31	GA	WTW	NF
Dickinson et al. 2013	113	.24	1.00	.24	GA	DS	NF
Dodd et al. 1977	604	−.16	.71	−.23	FD	WTP	F
Dvorak & Simons 2009	180	.29	.98	.29	GM	WTW	NF
Epstein et al. 2003	17	−.48	1.00	−.48	GA	WTW	F
Forzano & Chelonis 2010	11	−.80	1.00	−.80	GA	TD	F
Gailliot et al. 2007 (4)	12	.56	.97	.57	GM	WTW	NF
Gailliot et al. 2007 (5)	23	.45	.97	.46	GM	WTW	NF
Gailliot et al. 2007 (6)	17	.43	.97	.44	GM	WTW	NF
Gailliot et al. 2007 (9)	18	.62	1.00	.62	GA	WTW	NF
Geeraert & Yzerbyt 2007	44	.28	1.00	.28	GA	WTW	NF
Gilbert et al. 2002	222	−.16	1.00	−.16	GA	WTP	F
Hoefling & Strack 2010	59	−.32	.71	−.45	FD	TD	F
Kirk & Logue 1997	14	−.53	1.00	−.53	GA	TD	F
Kuhn et al. 2014	149	−.07	1.00	−.07	GA	TD	NF
Li 2008 (1)	49	−.32	.82	−.39	C	TD	NF
Li 2008 (2)	36	−.33	.82	−.40	C	TD	NF
Logue & King 1991	19	−.07	.71	−.09	FD	TD	F
Masicampo & Baumeister 2008	60	.21	1.00	.21	GA	DS	NF
McMahon & Scheel 2010	45	.38	1.00	.38	GA	DS	NF
Mela et al. 1996	96	−.12	.71	−.17	FD	WTP	F
Nasser et al. 2008	12	−.69	1.00	−.69	GA	WTW	F
Nederkoorn et al., 2009 (2)	94	−.19	.63	−.30	H	WTP	F
Nisbett & Kanouse 1969	134	−.18	.71	−.25	FD	WTP	F
Petersen et al. 2014 (1)	34	.34	.71	.48	FD	WTP	NF
Rasmussen et al. 2010 (nonfood)	53	−.13	.71	−.18	FD	TD	NF
Rasmussen et al. 2010 (food)	53	−.25	.71	−.35	FD	TD	F
Raynor & Epstein 2003	40	−.40	1.00	−.40	GA	WTW	F
Saelens & Epstein 1996	16	−.56	.63	−.89	H	WTW	F
Steinberg & Yalch 1978	30	−.18	1.00	−.18	GA	WTP	F
Tom & Rucker 1975	40	−.60	1.00	−.60	GA	WTP	F
Tom 1983	56	−.31	.71	−.44	FD	WTP	F
Wang & Dvorak 2010	65	−.23	.98	−.23	GM	TD	NF
Aarøe & Petersen 2013	104	.18	.97	.19	GM	WTP	NF

Note. C = cephalic phase manipulation; FD = food deprivation; GA = glucose administration; GM = glucose measurement; H = hunger score; DS = decision style; WTP = willingness to pay; WTW = willingness to work; TD = time discounting; F = food related; NF = not food related.

rected average effect size assuming publication bias. The trim-and-fill analysis resulted in a downward adjustment of the average effect size for most of the subgroups, yet none of the adjusted confidence intervals crossed zero (Table 5). We take this to suggest that even under the assumption of publication bias the results of the psychometric meta-analysis still provide a fairly accurate estimate of the average effect sizes.

Discussion

Using a psychometric meta-analysis (Hunter & Schmidt, 2004), we examined 36 studies providing 44 estimates of the effect of blood glucose on performance in four decision-making domains: studies in which participants made decisions of whether to spend or save money (willingness to pay), studies in which participants made decisions of whether to spend or save effort (willingness to work), studies in which participants made decisions between sooner-smaller and later-larger rewards (time discounting), and, finally, studies measuring the tendency to make deliberate versus intuitive decisions (decision style). We included only a single moderator in our analysis, whether the study in question was food related or not food related. The results are summarized in the first column of Table 1.
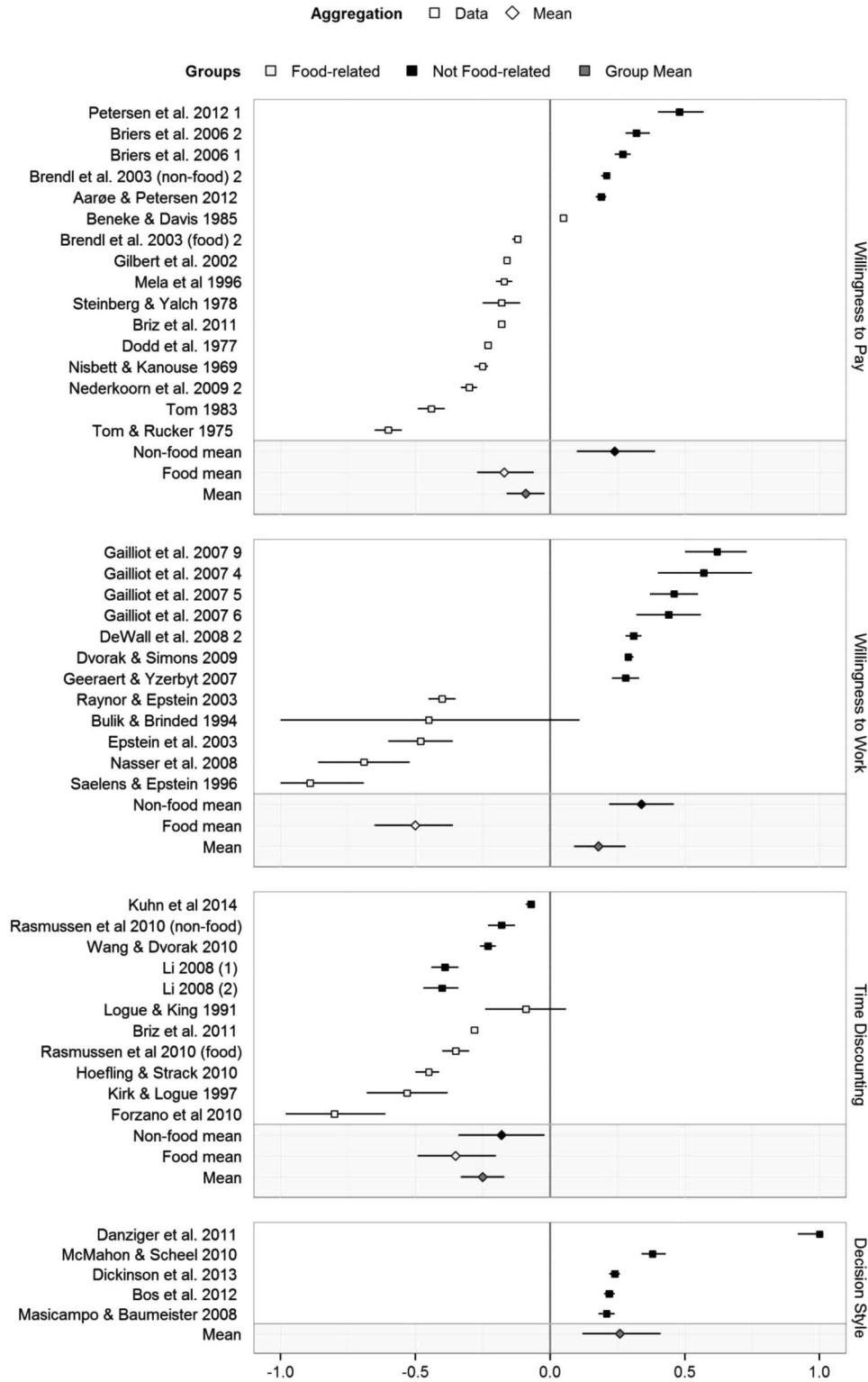
Figure 2. Forest plot of the unattenuated effect sizes for each of the four dependent variables. Error bars represent the 95% confidence intervals of the mean.

Table 5

Trim-and-Fill Publication Analysis of the Observed Effect Size Estimates

Group	Bias	Studies filled	$r_{observed}$	$r_{adjusted}$	CI$_{95}$ LL	CI$_{95}$ UL
Willingness to pay						
Food	Negative	4	−.16	−.11	−.19	−.03
Nonfood	Positive	2	.22	.19	.11	.28
Willingness to work						
Food	Negative	1	−.48	−.44	−.60	−.26
Nonfood	Positive	2	.33	.31	.21	.40
Time discounting						
Food	Positive	2	−.29	−.22	−.03	−.40
Nonfood	Positive	2	−.17	−.13	−.01	−.24
Decision style						
Nonfood	None	0	.31	.31	.13	.47

Note. bias = expected direction of publication bias; studies filled = number of studies imputed; $r_{observed}$ = attenuated effect sizes; $r_{adjusted}$ = effect sizes after imputation; CI$_{95}$ LL = lower limit of the 95% confidence interval of the adjusted estimates; CI$_{95}$ UL = upper limit of the 95% confidence interval of the adjusted estimates.

Summary of Results

The analysis of willingness to pay revealed a small negative main effect of blood glucose. The moderator analysis, however, revealed a significant negative effect of blood glucose on willingness to pay for food related tasks and a significant positive effect for tasks that are not food related. This means that *low blood glucose increases the willingness to spend money on food but lowers the willingness to spend money on anything not food related.*

The meta-analysis of the willingness to work studies revealed a similar pattern to the willingness to pay studies, the main difference being much larger effect sizes. This means that *low blood glucose increases the willingness to work on food related tasks but decreases the willingness to work on any other task.*

The analysis of time discounting revealed a significant, negative main effect of blood glucose levels. There was no significant difference between the food- and nonfood-related tasks. However, the moderator did reduce the pseudo-I^2, and there was no overlap in the credibility intervals of the two moderator groups, which for all practical purposes suggests a moderator effect. This means that *low blood glucose increases the future discount rate for food and to a lesser extent the discount rate for nonfood.*

The analysis of decision style was by far the smallest and included five studies, all of which were coded as not food related. The analysis revealed a significant positive effect of blood glucose levels on decisions style meaning that *low blood glucose increases the tendency to make intuitive rather than deliberate decisions on tasks that are not food related.*

Two studies were identified looking at the effect of blood glucose on decision making under risk (Levy, Thavikulwat, & Glimcher, 2013; Symmonds, Emmanuel, Drew, Batterham, & Dolan, 2010). Given the low number of studies, we decided not to include these studies in the quantitative synthesis. However, because the studies are relevant according to the inclusion criteria, we discuss them here.

The only theory making clear predictions about decision making under risk is optimal foraging theory. At the center of the theory is the principle of the budget rule, which proposes that animals under negative energy budgets will shift from risk averse to risk seeking.

If we assume that human decision makers behave toward monetary resources in a similar way as to food resources (Pietras & Hackenberc, 2001; Pietras et al., 2008), this leads to the prediction that decreasing levels of blood glucose should increase the risk taking for both food and money. The two studies on decision making under risk demonstrate this effect, showing that decision makers with low levels of blood glucose tend to make riskier choices when the outcome is either food or money.

Model Performance

How well did the four models do, across measures, in correctly predicting the pattern of findings observed? As discussed previously, not all models make predictions for each type of dependent measure and, further, some predictions are subject to a certain amount of debate. Furthermore, we have no results to report for one cell of the matrix: decision style tasks with food-related dependent measures. Still, we will attempt to summarize how well each model fared.

As discussed previously, the ego depletion and dual systems models make similar predictions, thus we evaluate the two models jointly. The main assumption of these models is that low levels of blood glucose create a fuel shortage in specific parts of the brain, particularly those areas related to the operation of the "rational" System 2. The deactivation of System 2 leads to a *general* loss of self-control, which, in the context of our dependent variables, means a general tendency to be lazy; that is, a lower willingness to work, a greater willingness to pay, higher time discounting, and the inability to make deliberate "thoughtful" decisions.

The meta-analytic results are in conflict with the two first predictions. The strength of the food moderator for willingness to work and willingness to pay undermines the prediction that the effect of blood glucose will be general. The time discounting results similarly suggest a moderation by food, albeit a smaller one. For decision style, the ego depletion/dual systems model predicts a general decrease in deliberation as a function of lower blood glucose levels. The observations are consistent with this prediction, but it is important to note that we have observations in only the nonfood domain; from our results, we cannot determine whether there is a moderator effect for this measure as well.

Overall, the predictions of the ego depletion/dual systems models fail in three out of the four domains we investigated. An alternative interpretation is to see the observations independently, in which case the models achieve five out of seven correct predictions. However, on this interpretation, the model achieves correct predictions inconsistently, correctly predicting an effect of blood glucose on willingness to work for nonfood and willingness to pay for food.

The visceral influences model assumes that low blood glucose levels cause the sensation of hunger and the motivation to seek food to alleviate this feeling. In the context of our dependent variables, this leads to seven predictions. First, lower blood glucose is predicted to increase willingness to work and willingness to pay for food while decreasing for nonfood. Second, time discounting is predicted to increase for food and decrease for nonfood. Finally, decision style is predicted to become more intuitive and less deliberate as a function of lower blood glucose.

Comparing these predictions with the observations suggests an overall high level of accuracy: six out of seven correct predictions. With respect to decision style, the model does not make particularly clear predictions and, as discussed previously, we interpret the model as predicting less deliberation for both food and nonfood. Future theoretical refinement and additional empirical work will be needed to arbitrate this issue. Overall, however, the model performs exceedingly well, making more predictions than the other models yet achieving a high level of accuracy.

Finally, optimal foraging models assume that evolution has shaped humans and other animals to respond to low levels of blood glucose by increasing foraging behaviors and, if necessary, incur costs and risk to obtain food. In the context of our dependent variables, this leads to the predictions that lower blood glucose increases willingness to work and willingness to pay for food; these effects should be reversed for nonfood. Optimal foraging models are more or less silent regarding time discounting and decision style. Comparing the predictions with observations, all four predictions match the data. A fifth prediction, that low blood glucose increases risk taking, also seems to match the findings of the two studies included in the qualitative synthesis, though, for reasons described previously, we do not include this prediction in the tally. In sum, the optimal foraging model makes fewer predictions than any of the other models, but achieves the best accuracy overall.

To conclude, we find that no single theory provides an unambiguous and accurate account of all the effects of blood glucose on decision making. However, the results clearly indicate that the two signaling models fare better than the ego depletion/dual systems model.

Implications

The present analysis suggests, then, the correct explanation for the effects documented are not to be found in resource models or dual systems models. The poor performance of the resource model is consistent with the growing worries about both the empirical and conceptual shortcomings of the resource model (Beedie & Lane, 2012; Job et al., 2013; Kurzban, 2010; Lange & Kurzban, 2014; Molden et al., 2012; Sanders et al., 2012). Our view is that the present findings add additional weight to the notion that there is little to be gained by further inquiry into the glucose as willpower

fuel model. This line of work should be abandoned in favor of more productive avenues.

Several predictions of dual systems models are, similarly, not borne out. Given the broad application of such models, one might suggest that the present context, effects of glucose, represents a boundary on the applicability of these sorts of models, rather than undermining such models generally. To retain confidence in dual systems models in this way, a principled explanation must be provided for why predictions derived from these models are not reflected in the patterns of data we observed. Absent such explanations, we take the position that the present results indict dual systems models to some extent.

More positively, the results reinforce prior suggestions (Green et al., 1997; Hagger, Wood, Stiff, & Chatzisarantis, 2010; Kurzban, 2010; Gibson & Green, 2002; Messier, 2004; Rogers & Lloyd, 1994; Wang & Dvorak, 2010) that concentrations of glucose molecules constitute information that is used for adaptive decision making. There is little dispute that glucose molecules supply energy from their chemical bonds for important processes, including providing the energy for the mechanical motion of the muscles, the electrical activity of neurons, and so forth. Glucose molecules are, more or less literally, a fuel for such processes. However, because glucose is so important to human functioning in its role as a fuel, it should be expected, from a functional perspective, that careful track should be kept of the present supply—just as fuel gauges do in vehicles—and that decisions should be made based on the present measurement—just as drivers are more likely to search for and stop at fueling stations as the fuel gauge dips toward empty.

That is, we think that these results reinforce the view that the proper way to think about the role of glucose in decision making is to consider the body's measurement of glucose as an input that guides adaptive behavior. Low glucose levels cause the sensation of hunger and motivate feeding-related behaviors at the expense of other potential priorities. The present results are continuous with these prior findings, suggesting that levels of glucose influence the willingness to work and the willingness to pay not *in general* but *in particular* in the context of food.

This interpretation aligns with recent findings investigating the effect of swishing glucose solutions in the oral cavity. If measurements of glucose are the key factor influencing behavior, then the detection of glucose in the mouth might exert an influence on decision making, even when the solution is not consumed. Kurzban (2010), in discussing the role of glucose in self-control, pointed to findings in the exercise literature showing that performance on physical tasks (e.g., cycling; Chambers, Bridge, & Jones, 2009) can be improved by having subjects gargle, but not swallow, sugar solutions. Since then, this idea has been investigated in the context of self-control tasks, and, in parallel to the exercise finding, simply swishing a glucose solution can have effects previously reported for subjects who consume such drinks (Hagger & Chatzisarantis, 2013; Molden et al., 2012).

This interpretation also resonates in certain respects to the role of physiological resources in the context of physical, as opposed to mental exertion. Research in the literature on exercise physiology suggests that while resources used during exercise are, of course, consumed during exertion, the reason that people are unable to continue exerting physical effort is not because of the lack of these resources (Gibson & Noakes, 2004). Instead, according to the so-called "Central Governor Theory" (Noakes, Peltonen, & Rusko,

2001), the cause of the reduction in the ability to continue exertion is signals from the central nervous system. The central nervous system, on this view, is monitoring the state of the organism, working to maintain homeostasis (Gibson & Noakes, 2004). The inability to continue exercise, then, is related to the reduction in resources, but is not caused by it. Something similar might be occurring with glucose levels and the kinds of decision making tasks discussed here (Evans, Boggero, & Segerstrom, 2015). According to this view, there is more than sufficient glucose for all necessary mental operations more or less at all times (Beedie & Lane, 2012); the level of glucose is, again, a measurement used as an input, not a constraint on attention, computations, or anything else.

Finally, we note that the present results might be felicitously considered in the context of broader discussions of the specificity of computational mechanisms (Tooby & Cosmides, 1992). Our read of the evidence presented in this article is that low glucose levels do not lead to a change in decision making *as a general matter*, as might be expected from the point of view of theories that propose that performance on many tasks is dependent on a broadly required domain general resource, such as glucose, or dual systems models, that might be taken to imply that low glucose levels lead to System 2 (impatient, heuristic) processes, *in general*. Instead, it appears that blood glucose has domain-specific effects, influencing decision making differently depending on the relevance of the situation to acquiring food.

Theoretical Perspectives and Future Research

In this section, we ask two questions: What type of theory or model could account for the present findings and what novel predictions would it make? The framework of Loewenstein provided the most accurate predictions, and a natural path is therefore to extend this framework. In particular, an important addition to the visceral factors approach would be a principled way to determine the relationship between particular goods and particular visceral factors. Loewenstein remains silent about what defines visceral factors, on how decision makers know whether a good is relevant to the visceral factor, and on why there are visceral factors at all. Without a theory about this it is difficult to make predictions beyond the examples in Loewenstein's paper. An important step would be to extend Loewenstein's ideas with a process model account (Jarecki, Tan, & Jenny, 2015). One promising process model, which Loewenstein also points to (Loewenstein, 2010), is the evolutionary theory of emotions by Cosmides and Tooby (2000). The authors provide a clear definition of and boundary conditions for emotions, which encompasses Loewenstein's term "visceral factors" and fluctuations in blood glucose covered in this article:

> To behave functionally according to evolutionary standards, the mind's many subprograms need to be orchestrated so that their joint product at any given time is functionally coordinated [. . .] This coordination is accomplished by a set of superordinate programs - the emotions. They are adaptations that have arisen in response to the adaptive problem of mechanism orchestration [. . .] The conditions or situations relevant to the emotions are those that (1) recurred ancestrally; (2) could not be negotiated successfully unless there was a superordinate level of program coordination [. . .]; (3) had a rich and reliable repeated structure; (4) had recognizable cues signaling their presence; and (5) were of a type in which an error would have resulted in large fitness cost.

We sketch a formal process model in Appendix C. The model, we believe, not only explains results obtained to date, but also makes some novel predictions. For example, the model suggests that low levels of blood glucose will increase the willingness to work for money, but to a smaller extent than for food (assuming immediate exchangeability for food). Similarly, our model suggests that low glucose will increase the willingness to exert mental effort, that is, make deliberate decisions, for food as well as money, but this increase will be smaller for money than for food, again assuming money can be readily exchanged for food. Last, the model suggests that low glucose will lead to decreased time discounting of nonfood goods. We look forward to tests of these predictions, as well as theoretical refinements.

Limitations and Generalizability of Findings

Beyond the theoretical implications, the current findings also have many practical implications for different areas such as policy making, business, and self-regulation. For this reason, we wish to point out certain limitations to the generalizability of the findings.

First, it is worth noting that the results apply only to those populations who can be said to have a normal response to fluctuations in blood glucose. That is, all participants who were diagnosed with diabetes, eating disorders, or were clinically obese were excluded from the analyses. These groups may respond differently to fluctuations in blood glucose.

Second, the results may be limited with respect to the range of blood glucose levels. Very few studies reported the absolute level of blood glucose concentration. No studies reported participants suffering from either hyper- or hypoglycemia during the experiment, which suggests that the range of blood glucose concentrations in the identified studies was bounded between approximately 3 to 12 mmol/L. This means that the conclusions from our meta-analysis only apply to the normal range of glucose concentrations and, furthermore, that the effect sizes concern a change in blood glucose not an exact level. Also, it is worth noting that there is no particular reason to believe that the effect of blood glucose on decision making is necessarily monotonic.

Finally, it is important to point out that the effect size estimates should be interpreted with some caution. For some moderator subgroups, only a small number of studies were available, which makes the estimation less reliable because of second order sampling error (Hunter & Schmidt, 2004). However, this problem is considerably alleviated if generalizations are based on the causal model drawn from our findings. Generalizations should in any case be based on a causal model, such as the one suggested previously, rather than on extrapolation of effect size estimates (Cooper et al., 2009).

Concluding Remarks

The results of the meta-analysis lead us to believe that peripheral glucose levels do seem to exert effects, in some way, on a number of decision-making tasks. Having said that, we view no extant proposal as having survived the analysis; in each case, at least one prediction fails. The view from optimal foraging theory was not falsified, but that framework, in our view, offers the fewest predictions in terms of the work that we reviewed.

It is, of course, possible, even likely, that the systems in question are sufficiently complex that there will be no single explanation

that can handle the diversity of effects of blood glucose on decision making. This would not be very surprising insofar as caloric state is a crucial biological variable, and the internal measurement of the organism's current need for food is likely to serve as an input to any number of decision-making systems, upregulating some, down-regulating others, and so on. We look forward to additional work addressing these complex issues.

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Appendix A

Results Excluding Imputed Studies

Group	K	N	r	SD_r	ρ	SD_ρ	CV_{95} LL	CV_{95} UL	CI_{95} LL	CI_{95} UL	Pseudo-I^2
All studies	40	3,845	−.04	.21	−.03	.24	−.51	.45	−.07	.01	79%
Willingness to pay	14	2,439	−.07	.14	−.09	.18	−.44	.26	−.16	−.02	76%
Food	10	2,177	−.11	.09	−.15	.12	−.39	.08	−.23	−.07	63%
Nonfood	5	411	.22	.00	.24	.00	.24	.24	.10	.39	0%
Willingness to work	12	444	.17	.33	.18	.30	−.40	.77	.09	.28	76%
Food	5	91	−.47	.10	−.50	.00	−.50	−.50	−.65	−.36	0%
Nonfood	7	353	.33	.07	.34	.00	.34	.34	.22	.46	0%
Time discounting	9	654	−.21	.10	−.25	.09	−.42	−.08	−.33	−.17	29%
Food	5	355	−.24	.11	−.35	.00	−.35	−.35	−.46	−.24	0%
Nonfood	4	299	−.18	.08	−.18	.05	−.28	−.08	−.30	−.05	16%
Decision style	5	308	.27	.10	.26	.00	.26	.26	.12	.41	0%

Note. k = number of studies; N = sample size; r = attenuated effect size; SD_r, = standard deviation of the attenuated effect size; ρ = unattenuated effect size; SD_ρ, = standard deviation of the unattenuated effect size; CV_{95} LL = lower limit of the 95% credibility interval; CV_{95} UL = upper limit of the 95% credibility interval; CI_{95} LL = lower limit of the 95% confidence interval; CI_{95} UL = upper limit of the 95% confidence interval; pseudo-I^2 = within-group heterogeneity.

Appendix B

Results When Imputed Studies Are Set to Zero Effect Size, $r = 0$

Group	k	N	r	SD_r	ρ	SD_ρ	CV_{95} LL	CV_{95} UL	CI_{95} LL	CI_{95} UL	Pseudo-I^2
All studies	44	4,196	−.03	.21	−.03	.24	−.49	.44	−.08	.02	78%
Willingness to pay	15	2,535	−.07	.14	−.09	.18	−.43	.26	−.15	−.02	75%
Food	11	2,273	−.10	.09	−.15	.12	−.38	.08	−.22	−.07	61%
Nonfood	5	411	.22	.00	.24	.00	.24	.24	.10	.39	0%
Willingness to work	12	444	.17	.33	.18	.30	−.40	.77	.09	.28	76%
Food	5	91	−.47	.10	−.50	.00	−.50	−.50	−.65	−.36	0%
Nonfood	7	353	.33	.07	.34	.00	.34	.34	.22	.46	0%
Time discounting	10	707	−.20	.11	−.24	.09	−.41	−.06	−.31	−.16	29%
Food	6	408	−.21	.13	−.31	.08	−.45	−.16	−.41	−.20	18%
Nonfood	5	352	−.15	.10	−.16	.04	−.24	−.09	−.27	−.05	9%
Decision style	5	308	.27	.10	.26	.00	.26	.26	.12	.41	0%

Note. k = number of studies; N = sample size; r = attenuated effect size; SD_r, = standard deviation of the attenuated effect size; ρ = unattenuated effect size; SD_ρ, = standard deviation of the unattenuated effect size; CV_{95} LL = lower limit of the 95% credibility interval; CV_{95} UL = upper limit of the 95% credibility interval; CI_{95} LL = lower limit of the 95% confidence interval; CI_{95} UL = upper limit of the 95% confidence interval; pseudo-I^2 = within-group heterogeneity.

(Appendices continue)

Appendix C

A Process Model of Blood Glucose Effects

We propose that the relationship of a good or action x_i to an emotion α cannot be explained without reference to an adaptive problem. The adaptive problem triggers an emotion which in turn prioritizes and directs the organism toward actions and objects that alleviate the adaptive problem. An action or good is prioritized if it has served to alleviate the adaptive problem in the evolutionary history of that organism. The emotion also recruits higher order cognitive processes such as causal reasoning to extend the set of possible actions that may alleviate the adaptive problem. To make the framework more tractable we propose that an organism under the influence of an emotion will classify goods and actions as primary instrumental I_1, that is, those that alleviate the adaptive problem immediately, secondary instrumental I_2 that can be exchanged for primary instrumental goods and thereby alleviate the adaptive problem, and tertiary instrumental I_3, that is, those goods and actions that cannot be exchanged and therefore have zero instrumentality to alleviate the adaptive problem.

The appropriate response to an adaptive problem is to seek out primary instrumental goods or if none are available secondary instrumental goods, given that these can be exchanged for primary goods fast enough, and avoid tertiary goods. To an external observer the organism will respond as if the value v_i of good x_i is increasing or decreasing under the influence of the emotion α. For any emotion there is a reference level α^* at which the instrumentality of goods to that emotion has no effect on the value of goods independent of the time t of consumption.

$$v(x, \alpha^*, I_1, t) \approx v(x, \alpha^*, I_2, t) \approx v(x, \alpha^*, I_3, t)$$

At a high level of the emotion α' where $\alpha' > \alpha > \alpha^*$ the value of goods change relative to the reference level depending the instrumentality of the good. Primary goods increase in value and secondary goods increase in value but to a smaller extent and only if they can be exchanged for primary goods. Tertiary goods lose value relative to the reference level (see Figure 3, left).

$$v(x, \alpha', I_1, t) > v(x, \alpha', I_2, t) > v(x, \alpha^*, I_i, t) > v(x, \alpha', I_3, t)$$

Current emotions have a weak effect on the value of goods that will be consumed in the future, $t > 0$ (Figure 3, right).

$$v(x, \alpha', I_1, t_1) \geq v(x, \alpha', I_2, t_1) \geq v(x, \alpha^*, I_i, t_1) \geq v(x, \alpha', I_3, t_1)$$

The effect size ES of an emotion α on the value of good x with instrumentality I consumed at time t can be operationalized as the standardized mean difference.

$$ES(x, \alpha', I, t) = \frac{v(x, \alpha', I, t) - v(x, \alpha', I, t)}{SD(v)}$$
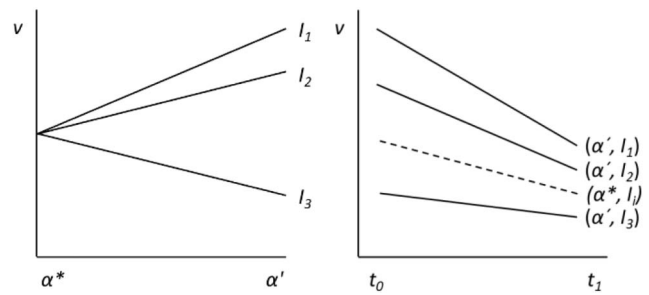

Figure 3. The effect of an emotion α on the value v of goods and actions with different levels of instrumentality I_i at time t = 0 (left) and time t > 0 (right). The dashed line indicates the reference level of the emotion at which it has no influence on valuation.

For willingness to pay which is an exchange of one good x_1 for another good x_2 the effect size of the emotion is the difference in value incurred on the two goods that are exchanged.

$$ES(x_1, \alpha', I, t) - ES(x_2, \alpha', I, t)$$

For time discounting which can be (crudely) operationalized as the slope between the current value and the future value of a good, the effect size of the emotion is the difference in slopes under two different levels of the emotion.

$$ES(x_1, \alpha, I, t) - ES(x_2, \alpha', I, t)$$

Under these assumptions we can predict the direction and magnitude of effect sizes of an emotion on willingness to work, decision style (which we conceptualize as willingness to think), and time discounting for the three classes of goods.

$$ES(x, \alpha, I_1, t) > ES(x, \alpha, I_2, t) > 0 > ES(x, \alpha, I_3, t)$$

For willingness to pay, we assume that money is a secondary good that can be exchanged for either a primary or tertiary good. This leads to the prediction that:

$$ES(x, \alpha, I_1, t) > 0 > ES(x, \alpha, I_3, t)$$

Because the effect size for willingness to pay is the difference in effect sizes of the emotion on good x_1 and good x_2 it also follows that the magnitude of effect sizes for primary and secondary goods are different.

$$|ES(x, \alpha, I_1, t)| < |ES(x, \alpha, I_3, t)|$$

(*Appendices continue*)

If we assume that low levels of blood glucose is an adaptive problem as defined by Cosmides and Tooby (2000) that trigger an emotion, that food is a primary good, money a secondary good, and all other goods that cannot be exchanged for food are tertiary goods then it follows that low levels of blood glucose will:

- Increase the willingness to work for food.
- Decrease the willingness to work for nonexchangeable, nonfood goods.
- Decrease the willingness to think for nonexchangeable, nonfood goods.
- Increase the willingness to pay for food.
- Decrease the willingness to pay for nonexchangeable, nonfood goods.
- Increase time discounting for food.
- Increase time discounting for money, but less so than for food.

In addition, the framework predicts that since both food and money increase in value under low levels of blood glucose, but nonfood decrease in value:

- The effect size magnitude is larger for willingness to pay for nonfood than for food.

The first seven predictions correspond to the seven cells that we have observed in the meta-analysis (Table 2). Prediction eight is also observed.

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