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Examing the Effects of Energy Deprivation on the Strength Model of Self-Control: An Imposition Theory

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Abstract

The strength model of self control suggests exerting self-control consumes an energy resource that is depleted in subsequent tasks. Past research is equivocal whether such depletion happens and whether glucose can reverse it. We proposed an imposition theory to reconcile the contradiction: (1) energy deprivation is a prerequisite condition; (2) awareness of deprivation modulates the extent of depletion. The results suggested that rats showed more self-control depletion and performance across different conditions was more consistent when food deprived compared to when not. There was also a marginal effect of awareness of the deprivation.

Examining the Effects of Energy Deprivation on the Strength Model of Self-Control: An Imposition Theory

Self-control, the idea of effortful regulation of the self by the self, is widely studied in the social sciences (Duckworth, 2011). It is often applied in a social dilemma that contains a conflict between immediate consequences and delayed consequences: immediate consequences are usually more powerful than delayed ones as the value of the reinforcer decreases as delay increases (Ainslie, 1975). Therefore, self-control is used to make choices between immediate pleasure and later consequences in real life. A "hot-and-cool" system is proposed to explain how people are able to delay immediate pleasure (Metcalfe & Mischel, 1999). The cool system refers to the cognitive system, which incorporates knowledge and cognitive thinking, while the hot system refers to the emotional system, which is controlled by innate emotions, fears and passions (Metcalfe & Mischel, 1999). When the hot system overrides the cool system, people struggle to delay short-term rewards (Metcalfe & Mischel, 1999).

Studies have shown that being able to delay immediate pleasure in order to gain future consequences is essential for human development (Mischel, Shoda, & Rodriguez, 1989). Children who exhibited more self-control were described by their parents as more socially competent, verbally fluent and better at dealing with frustration and stress in adolescence (Mischel et al., 1989). On the contrary, the inability to control oneself can lead to maladaptive behaviors, such as not acquiring long-term jobs, not getting and retaining friends, failing in long-term relationships and committing crimes (Gottfredson & Hirschi,

1990). Self-control is not only important for humans' development, but also evolutionarily crucial for animals. Animals use self-control to avoid feeding when a higher-ranking individual is present, share food with kin or mates and search for food in a new area rather than an old site in the wild (MacLean et al., 2014).

Self-control is well studied in experiments because of its importance in understanding human and animal behavior. Past experimental designs usually involved a required long delay of reinforcement (Mischel et al., 1989), high effort (Eisenberger, Mitchell, & Masterson, 1985), or a delivery of punishment (Dollard & Miller, 1950) as the measurement of self-control, as they measured the ability to endure the increased costs in order to reach a desirable goal. The most commonly used design to study self-control in humans and animals is the *delay of gratification* task (Mischel et al., 1989). The *delay of gratification* task asks the subject to choose between a smaller sooner reward and a larger later reward (Mischel et al., 1989). Self-control in this task means choosing a larger later reward, while impulsiveness means choosing a sooner, smaller reward. The *marshmallow task* is a common example of a *delay of gratification* task. This task requires preschoolers to wait until the experimenters return in order to gain a preferred treat (marshmallow) or to end the session at an earlier point and get a less preferred one (pretzel) (Mischel et al., 1989).

The *delay of gratification* task has also been used in other animals like dogs (Miller, Pattison, DeWall, Rayburn-Reeves, & Zentall, 2010), pigeons (Jackson & Hackenberg, 1996), and rats (Van Haaren, Van Hest, & Van De Poll, 1998). For example, rats in an experiment had to choose between pressing an upper lever that gave an immediate access to

a small amount of food and pressing a lower lever that resulted in a 6-second delay followed by a large amount of food (Van Haaren et al., 1998). In another study, pigeons received a more preferred reinforcer if they waited for a trial to end or a less preferred reinforcer if they chose to peck the key (Grosch & Neuringer, 1981). Multiple studies have shown that both humans and other animals are able to exert self-control (Grosch & Neuringer, 1981; Mischel et al., 1989; Miller et al., 2010; Jackson & Hackenberg, 1996; Van Haaren et al., 1998).

Because the ability of self-control is not limited to humans, this shared ability indicates a possible neuronal basis of self-control that could apply both to human and non-human animals. Past studies have emphasized the important role of prefrontal cortex and the limbic system on the ability of self-control. Rats showed more impulsivity when their orbitofrontal cortex and amygdala was disconnected (Churchwell, Morris, Heurtelou, & Kesner, 2009). An fMRI study localized frontal brain regions in dogs when they inhibited their behaviors (Cook, Spivak, & Berns, 2016). In pigeons, nidopallium caudolaterale (NCL), which is comparable to the prefrontal cortex in humans, were found fired when pigeons chose a larger delayed reward (Kalenscher, Windmann, Diekamp, Rose, Gu, & Colombo, 2005). Another study done on rhesus monkeys has been associated the orbitofrontal cortex with the ability of self-control (Roesch & Olson, 2005). Furthermore, with neuroimaging techniques including magnetic resonance imaging (MRI), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI) in humans, the prefrontal cortex shows more activity in the formation of self-control while the limbic system that is responsible for rewards and emotions becomes more active in decisions involving immediate reward (Goldberg, 2001;

Miller & Cohen, 2001; Heatherton & Wagner, 2011). Therefore, evidence from brain studies aligns with the "hot-and-cool" system theory: limbic system represents the hot system because it correlates more with making a choice involving immediate reward; prefrontal cortex represents the cool system because it involves in choosing delayed rewards (McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007).

The prefrontal cortex can be separated into three sections: the dorsolateral prefrontal cortex (DLPFC), the orbitofrontal cortex (OFC), and the medial prefrontal cortex (MPFC), each of which contributes to the formation of self-control. DLPFC is associated with behavioral inhibition, cognitive control, information-processing skills and working memory; OFC helps maintain goal-oriented behaviors and regulate complex decision makings and emotions; MPFC is believed to modulate attentions (Beaver, Wright, & Delisi, 2007). The functions associated with the dorsolateral prefrontal cortex, orbitofrontal prefrontal cortex and medial prefrontal cortex together are referred to as "executive functions" (Goldberg, 2001). Self-control is often viewed as one type of executive functions that is located in the prefrontal cortex (Beaver et al., 2007). What's more, functional magnetic resonance imaging (fMRI) also shows that there is a stable individual difference in self-control that can last across the lifespan (Casey et al., 2011). People whose brain recruits ventral striatum more during the *delay of gratification task* result in low self-control (Casey et al., 2011). This individual difference should thus be taken into consideration when other potential factors that can influence self-control are studied among separate groups of participants.

The Strength Model of Self-control

A large body of studies has been focused on understanding how self-control is exerted. Baumeister, Bratslavsky, Muraven, and Tice (1998) proposed the energy model of self-control, which is later referred to as the strength model of self-control as well (Baumeister, Vohs, & Tice, 2007). The model states that exerting self-control consumes an energy resource and results in short-term impairments (self-control depletion) in subsequent tasks; psychological factors like motivation can temporarily block the impairments (Baumeister et al., 2007).

From a metabolic perspective, self-control is a cognitive process that requires an energy source to maintain effective brain functions (Gailliot & Baumeister, 2007). The human brain, which constitutes of 2% of the body weight, consumes 20% of the body's energy (Dunbar, 1998). One primary candidate for such an energy is glucose, which is important for brain physiology. About 70% of the total body glucose metabolism is used by the brain (Mergenthaler, Lindauer, Dienel, & Meisel, 2013; Brandt, n.d.). Therefore, exerting self-control is believed to consume energy in the brain that is provided by glucose, because it is one kind of executive functions located in the frontal lobe of the brain (Beaver et al., 2007).

Studies have found a correlation between blood glucose level and self-control at a societal level (DeWall, Deckman, Gailliot, & Bushman, 2011). An interesting finding is that, after controlling for poverty, the prevalence of diabetes, which is characterized by the disability to metabolize glucose, has a positive correlation with violent crime rates in all 50 states in United States (DeWall et al., 2011). The prevalence of glucose-6-phosphate

dehydrogenase deficiency, a disorder that prevents people from metabolizing glucose, also shows a positive correlation with violent killing rates in both war and non-war situations in 122 countries (DeWall et al., 2011). Although these observational studies do not provide strong causal evidence, a model of self-control can be proposed based on the correlation, and further controlled experiments are needed to examine a causal relationship.

To test whether the causality between glucose levels and self-control is metabolic, glucose injection, including oral and intravenous, have been used. The control group is typically given a placebo treatment, which contains a sweetened but zero-calorie injection to exclude the effect of sweetness (Gailliot & Baumeister, 2007). Supporting evidence showed that going through a cognitive depletion task made participants quit faster and perform worse in subsequent cognitive tasks (Baumeister et al., 1998). Completing a cognitive depletion task also increased electromyography (EMG) activity, which is usually associated with stress and fatigue (Bray, Martin Ginis, Hicks, & Woodgate, 2008). Another study used fMRI to show that right middle frontal gyrus (rMFG), an area that plays an important role in self-control processes, was less active during the subsequent task after participants performed an attention-demanding task (MacDonald et al., 2000; Hedgcock, Vohs, & Rao, 2012).

A more thorough examination that involved nine studies also suggested that small tasks using self-control were able to impair the later control of thought and behavior (Gailliot et al., 2007). Blood glucose level also dropped after the human subjects performed tasks that required self-control, while glucose intake reduced self-control decrements (Gailliot et al.,

2007). Glucose consumption has shown to improve the ability of self-control after a depletion effect. Studies have indicated that consuming glucose restored effortful decision making processes in subsequent tasks after self-control had been depleted in the preliminary task (Baumeister et al., 1998; Masicampo, & Baumeister, 2008; Miller et al., 2010).

The causal relationship between self-control depletion and glucose level decrements has been shown from the studies discussed. It is likely that glucose consumption could enhance self-control abilities because increasing glucose levels in the blood can help cognitive functions in the brain (Gailliot & Baumeister, 2007). At the same time, the allocation hypothesis has explained the importance of glucose metabolism from another perspective, which states that glucose consumption does not directly facilitate the ability of self-control (Beedie, & Lane, 2012). Rather, the theory argues that a high availability of blood glucose allows the body to put more resources into doing self-control tasks by changing the priorities of cognitive functions, while a low availability makes the body reserve energy for urgent survival needs (Beedie & Lane, 2012). The allocation hypothesis supports the metabolic model in a way that it focuses on the physiological effect of glucose on humans' bodies.

Indirect evidence has also been found to support self-control depletion and the positive effect of glucose on cognitive functions. Aggressive behaviors, which can be viewed as an indirect indicator of self-control, have been assessed in several studies. It is shown that people whose self-control was depleted in the initial tasks behave more aggressively when being provoked compared to people whose self-control was not exerted (DeWall, Baumeister, Stillman, & Gailliot, 2007; Stucke & Baumeister, 2006). Aggression could also be restrained

by glucose among people with high trait aggression when they were provoked (New, 2004; Denson, von Hippel, Kemp, & Teo, 2010). After exerting self-control, people's ability to manage their intake of alcohol was impaired (Muraven, Collins, & Neinhaus, 2002). Other studies showed that sucrose drinks reduced prejudice and stereotyping, increased the willingness to help others (DeWall, Baumeister, Gailliot, & Maner, 2008) and increased working memory performance among subjects (Gailliot, Peruche, Plant, & Baumeister, 2009; Carter & McCullough, 2013).

Animal models provide support to the strength model of self-control as well. Honeybees after a 24-hour food deprivation preferred the smaller immediate option over the larger delayed option compared to those after 6 or 18 hours of food deprivation (Mayack & Naug, 2015). The causality between glucose consumption and self-control increments has also been studied in dogs. The group of dogs that were given glucose persisted longer in an unsolvable task than the group of dogs that were given a sugar-free placebo after both groups exerted self-control to sit still for 10 minutes (Miller et al., 2010). Another study indicates that the exertion of self-control impaired dogs' working memory on a subsequent searching task (Miller, 2013).

While it has been supported by both direct and indirect evidence, *the metabolic model* has been challenged by *the motivational model* to explain the effect of glucose on self-control. In *the motivational model*, psychological effect is valued over physiological effect. One experiment that assessed blood glucose levels with highly precise measurements did not find an increasing metabolism rate of carbohydrate (Molden et al., 2012). However,

the same study showed that simply rinsing the mouth with carbohydrate without injecting it could reduce the depletion of self-control (Molden et al., 2012; Hagger & Chatzisarantis, 2013). Research has also found that carbohydrate mouth rinse increased athletes' physical performance (Carter, Jeukendrup, & Jones, 2004). The evidence suggested that the replenishing effect of glucose on self-control depletion was not limited to glucose consumption.

The motivational model argues that sweet flavor can increase participants' motivation by activating brain areas associated with reward (Sanders, Shirk, Burgin, & Martin, 2012). From the biological viewpoint, rinsing the mouth with glucose has been found to activate the anterior cingulate cortex and the striatum, which are correlated with the inhibition of action and the postponement of immediate rewards, which indicates successfully exerting self-control (Chambers, Bridge, & Jones, 2009). The anterior cingulate cortex has been shown to be active in frequently used self-control tasks, like the Stroop color-naming task (Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000) and the hand grip strength task (Liu et al., 2003). The activation of the anterior cingulate cortex has been observed to decrease after performing on tasks requiring self-control (Hagger & Chatzisarantis, 2013). Nevertheless, rinsing the mouth with artificial sweeteners like saccharin has not been observed to have a replenishing effect on self-control. Artificial sweeteners activate separate taste receptors, which would not induce activation in the same brain regions as glucose does (Hagger & Chatzisarantis, 2013).

At the same time, assessing blood glucose levels does not necessarily provide sufficient evidence to support the lack of increasing glucose metabolism in the brain: because of the blood-brain barrier which restricts glucose transportation from blood to brain, local rates of glucose metabolism depends on functional activities performed in the brain (Mergenthaler et al., 2013). One study used fMRI to study the participants' brain activities by manipulating their sugar levels in the bloodstream intravenously (Page et al., 2011). Instead of providing energy, consuming glucose intravenously was shown by fMRI to modulate brain reward regions, which reduced stress hormones that were related to craving as well as stimulate medial prefrontal cortex, which was associated with behavioral inhibition (Page et al., 2011). Thus, while receiving glucose intravenously eliminated the influence of sweet flavor on human's motivation, fMRI data still suggested that the prefrontal cortex, which plays a crucial role in human's ability of self-control, was activated. It indicated that sweet flavor was not the only pathway to activate corresponding brain regions and circulating glucose levels in the brain might also be able to activate these regions (Page et al., 2011). At the same time, the study did not fully reject *the motivational model*: it did not suggest that the function of glucose injection is to make brain resource more available for the whole brain. Rather, it was consistent with the finding in *the motivational model* that self-control increased because brain areas associated with self-control were activated by glucose (Sanders et al., 2012).

Evidence supporting both *the motivational model* and *the metabolic model* has been found in the past research, which makes it a debating topic in studies of the strength model of self-control. As a result, there is no definitive conclusion on which mechanism best

explains the data. It is possible that the two mechanism might work together to show an increase in self-control.

Contradictory Results in Existing Studies

Not only is the underlying mechanism of self-control depletion unsettled, but there are also mixed results in past research about whether self-control can be depleted. At the same time, the effect of glucose consumption and rinsing is also controversial.

Some replications failed to show this depletion effect and/or failed to show the replenishing effect of glucose consumption even when using different tasks (Lange & Eggert, 2014; Xu et al, 2014; Lange, Seer, Rapior, Rose, & Eggert, 2014). When using a more precise measurement of the glucose level in the bloodstream by a glucose analyzer, researchers failed to show a decrease of the glucose level after exerting self-control (Molden et al., 2012). A replication conducted by Boyle, Lawton, Allen, Smith, and Dye (2016) did not support the replenishing effect of glucose on self-control depletion after rinsing the mouth with sweetener. Animal experiments conducted on capuchin monkeys indicated a limited depletion effect following prior self-control exertion in a food accumulation task, but task performance did not improve after consuming glucose (De Petrillo et al., 2015; Parrish, Emerson, Rossettie, & Beran, 2016). The experiment testing dogs' working memory, although indicating self-control depletion, showed no replenishing effect of glucose consumption (Miller, 2013).

Some studies show mixed results and imply that there may be psychological factors involved. One study, which observed self-control depletion after performing the initial task,

failed to replicate the enhancing performance in the subsequent task after consuming glucose (Kelly, Sünram-Lea, & Crawford, 2015). However, in the same study, it was observed that how motivated participants were when they completed the task played a role in alleviating the depletion in the subsequent task after prior self-control exertion. Another study supported the idea that highly motivated participants performed better on a subsequent task of self-control (Muraven & Slessareva, 2003). People's belief on whether self-control is a limited resource can also have an effect on the performance in the subsequent task after exerting self-control (Job, Walton, Bernecker, & Dweck, 2013). Subjects who self reported that self-control could be depleted performed worse after completing a self-control task compared to people who believed that self-control was unlimited (Job et al., 2013). How people perceived the self-control depletion task also affected the subsequent task performance (Clarkson, Hirt, Jia, & Alexander 2010). During one study, when subjects were instructed that the self-control task that they completed *energized and replenished* their cognitive ability, they persisted significantly longer on the following problem-solving task compared to people who were instructed that the self-control task *exhausted* one's cognitive ability (Clarkson et al., 2010).

Because of this inconsistency, whether the depletion effect exists and whether glucose has a replenishing effect on self-control depletion are still doubted and have become major controversies in this field.

Reconciling the Contradiction

As a large body of studies supports both sides of the strength theory of self-control, it becomes important to examine whether an underlying mechanism can reconcile the contradiction. Studies that directly measured blood glucose level after performing self-control tasks often required the subjects to avoid eating for three hours in order to have a low or more stable glucose level, which suggested that the initial energy level might play an important part in self-control depletion (Gailliot et al., 2007; Kurzban, 2010).

A closer look at the methodology of the studies revealed a potential explanation for the contradiction among studies. Although the methodology used varied in the number of subjects, types of depletion tasks, types of dependent tasks, and the amount of glucose consumed, one methodological manipulation was typically contradicting between most studies that support self-control depletion and the replenishing effect of glucose and studies that do not support that: the length of fasting. Experiments that required human subjects to be food deprived for over three hours yielded more supportive evidence of self-control depletion and showed a more replenishing effect of glucose in the subsequent tasks (see Table 1, Baumeister et al., 1998; Gailliot et al., 2007; Hagger & Chatzisarantis, 2013; Carter & McCullough, 2013; Dvorak & Simons, 2009). The experiments, which introduced indirect evidence of self-control depletion and glucose reimbursement by looking at aggression, prejudice and stereotyping, working memory, etc. required subjects to fast over three hours as well (see Table 1; Stucke & Baumeister, 2006; DeWall et al., 2007; Masicampo, & Baumeister, 2008; Gailliot et al., 2009; Denson et al., 2010).

At the same time, experiments that required human subjects to be food deprived for less than 2 hours yielded no significant results (see Table 2; Job et al., 2013; Lange & Eggert, 2014; Xu et al, 2014; Lange et al., 2014; Kelly et al., 2015).

The length of food deprivation was consistently different between the studies supporting and not supporting the strength theory of self-control. Such evidence suggests that energy depletion may be a necessary precondition in order to induce self-control depletion in subsequent tasks. According to the strength model of self-control, performing a cognitive task consumes the main energy source of the brain (glucose), which impairs the ability to perform subsequent cognitive tasks. It is likely that lengthening food deprivation makes less glucose available in the brain and therefore may induce a more obvious self-control depletion effect.

Neurophysiology studies also provide evidence that when subjects had fasted, blood glucose level fell more when the subjects needed to suppress their emotions in a given circumstance, which required inhibiting or modulating emotions and behaviors, another form of self-regulation (Dvorak & Simons, 2009). Another study also emphasized the potential effect of avoiding eating: Only with a recent fast was blood glucose level lowered after performing a self-control task (Kurzban, 2010). The necessity of food deprivation is implied by the allocation theory as well. Because a high availability of blood glucose allows the body to put more motivation into doing self-control tasks, a low availability caused by food deprivation may make the body reserve energy for urgent survival needs instead of for cognitive functions (Beedie & Lane, 2012).

A question that arises is why an approximate one-hour difference in the length of food deprivation in human subjects might have a significant effect on whether the experiments' results indicate self-control depletion. It is noticed that numerous studies used college students as subjects (Baumeister et al., 1998; Gailliot et al., 2007; Masicampo and Baumeister, 2008; Denson et al., 2010; Hagger & Chatzisarantis, 2013; Carter & McCullough, 2013; Lange & Eggert, 2014). It is possible that asking students to avoid eating for over three hours requires conscious effort from the students, but that asking students to avoid eating for one and a half or two hours fits more with students' normal schedule (e.g. withholding food during classes). Therefore, it suggests that being aware of food deprivation may play an important role in inducing self-control depletion.

Among the studies discussed above, there is one exception, in which human subjects went through self-control examination between 7:00 and 10:30 in the morning after an overnight fast, but the study did not support glucose as a self-control resource (Boyle et al., 2016). The testing time in this study is especially interesting: the testing happened after an overnight fast. As the fast happened during sleep, the argument could be made that participants in this study might not invest conscious effort during their fasting period.

Since most studies done on human subjects did not require a fast over three hours, we looked at studies conducted in animals, because they employed more varied fasting times in methodology, allowing further examination of the effect of food deprivation. A study done on honeybees directly addresses food deprivation and its relation with self-control. In the study, honeybees showed more impulsivity after a long deprivation (24 hours) compared to a

short deprivation (6 hours or 18 hours) (Mayack & Naug, 2015). Another study conducted with dogs fasted the subjects for four hours before testing and results indicated that giving glucose to dogs improved their performance in an unsolvable task (Miller et al., 2010). However, a similar study done in dogs did not show a replenishing effect of glucose; this study withheld the dogs' breakfast but did not require a fasting period (Miller, 2013). This lack of effect was replicated in an experiment conducted on capuchin monkeys, in which fasting was also done overnight and the monkeys maintained their typical dietary routine (Parrish et al., 2016). Another study with capuchin monkeys tested the monkeys' self-control before and after the major meal while maintaining their daily dietary routines; the study showed no depletion effect (De Petrillo et al., 2015).

The difference between fasting during the day and fasting during the dark-cycle seems to influence how both human and non-human subjects performed on subsequent self-control tasks after exerting self-control and consuming glucose. While a low energy state that is caused by food deprivation may play a necessary role in self-control depletion, the awareness of being depleted also seems to be important. It has been shown that psychological intervention, including self-affirmation, willingness, self-definition of willpower, is able to counteract self-control depletion (see Table 3; Schmeichel & Vohs, 2009; Hagger & Chatzisarantis, 2013; Job et al., 2013). Acting according to the current mental and physical states, especially when the resource is depleted, is evolutionarily important to both humans and animals (Schmeichel & Vohs, 2009). Therefore, whether a human or an animal is aware

of energy depletion may directly affect whether self-control depletion could be induced after exerting self-control and whether glucose consumption can counteract self-control depletion.

As a result, we proposed an imposition theory of self-control that aimed to reconcile the contradiction of self-control depletion and the replenishing effect of glucose in the past research: (1) being energy deprived is the prerequisite condition; (2) self-awareness of the deprivation modulates the extent.

Present study

The present study used rats, a commonly used animal in labs, to test the imposition theory of self-control. Rats have been shown to have the ability to choose a large but delayed reward over a small but immediate reward in multiple studies (Van Haaren et al., 1998; Mazur, 2012). Compared to humans, rats used in psychological experiments are raised in a homogeneous environment, which can give a more reliable result. Because rats reduce the various social, behavioral, and genetic difference that exists in humans, they allow highly controlled experiments to establish causal relationships between important variables (Blazer & Hernandez (Eds.), 2006). Therefore, using rats allowed the experimenter to precisely control over diet, the important independent variable in the current study.

At the same time, there has been very little empirical research on self-control depletion and glucose reimbursement regarding rats. Prior to this project, the strength model of self-control had not been tested on rats. Furthermore, there is a dearth of literature about the effect of glucose consumption on self-control in rats. An initial challenge was to design a self-control depletion task for rats since rats are unable to perform complex cognitive tasks

used in human experiments. Therefore, our first step was confronting the gap in the literature by building a new animal model. In a preliminary experiment (see Appendix A), we explored whether self-control in rats could be depleted and whether glucose could counteract the depletion effect. The *delay of gratification* task was used to measure self-control in the present study and water was used as the reinforcer. Although the depletion effect was not shown in the preliminary study, the pattern suggested a replenishing effect of glucose.

The study questioned the effectiveness of the self-control depletion task used and argued that there might be a ceiling effect as rats showed high baseline self-control. Therefore, other ways to consume mental resources were needed in order to induce self-control depletion in rats. Coping with stressful events requires self-regulation and, therefore, results in a worse self-control performance, because monitoring threatening stimuli requires more vigilance and attention that consumes mental resources (Muraven & Baumeister, 2000). Research has shown that, after exposure to unanticipated and uncontrollable noise, a type of stressor, rats performed worse in the subsequent cognitive tasks (Glass, Siger, & Friedman, 1969). In a followup to the preliminary study, a different depletion task (exposure to noise) was used and the delay before the delivery of a large reward was increased (Laske, 2016). Rats showed self-control depletion after being exposed to noise and glucose consumption counteracted the depletion effect (Laske, 2016).

The current study examined the influence of deprivation on the depletion effect of rats' self-control in order to test the imposition theory that aimed to reconcile the contradiction of self-control depletion and glucose reimbursement in the past research. The *delay of*

gratification task was used to measure self-control and water was used as the reinforcer. Because rats must experience water deprivation for them to be motivated enough to perform the task, which would result in depression of food intake, we thus introduced food deprivation on top of water deprivation (Strominger, 1947). Compared to water deprivation alone, food and water deprivation together aggravated the energy deprivation that rats experienced. What's more, as we proposed that self-awareness of the deprivation modulates the extent of self-control depletion and the replenishing effect of glucose, we also manipulated how aware of the food deprivation rats were in this study. We imitated the methodology used in capuchin monkeys by either fasting the rats during the day or during the night (De Petrillo et al., 2015; Parrish et al., 2016). It is worth noticing that, as nocturnal animals, rats have the opposite circadian rhythm compared to humans: they rest during the light period and are more active during the dark period (Roedel, Storch, Holsboer, & Ohl, 2006). *Ad libitum* rats consume the least amount of food during the first half of the light cycle and they consume the most amount of food during the first half of the dark cycle (Siegal, 1961). Therefore, rats should be less aware of the fast during the day than the fast during the night.

Though past research has reflected a contradiction in whether self-control depletion could be induced, few theories have aimed to reconcile this controversy. The goal of this experiment was to test whether the difference in methodology in the past studies led to the existing contradiction. In this experiment, we proposed that (1) rats' self-control would be depleted and glucose oral injection would reimburse self-control depletion; (2) rats would

show more self-control depletion and more replenishing effect of glucose if they were on the food deprivation compared to if they were not on food deprivation; (3) rats would show more self-control depletion and more replenishing effects of glucose if they were fasted during the night compared to if they were fasted during the day.

Method

Subjects

Sixteen naive female Sprague-Dawley rats bred in-house at Macalester College served as subjects. They were all approximately 100 days old at the beginning of the experiment. The rats were allowed access to food *ad libitum* except for the four test days and were housed in same-sex groups of two in a temperature- and humidity- controlled environment under a 12-h light/dark cycle (lights off at 8.00 P.M.).

Apparatus

Eight Coulbourn Instruments Large Modular Test Cages (Lehigh Valley, PA) comprised the test chambers used in the experiment. Each chamber was equipped with light mounted in the upper portion of the center of the modular wall (Coulbourn Instruments), a feeder device, and a dipper (0.6 ml) (BioServ, Frenchtown, USA) where water was provided. Two retractable levers (Med-Associates) were mounted horizontally and symmetrically in the lower panel and the dipper was mounted in the lower center panel. The reinforcer in the experiment was water.

A graphic state software (Coulbourn Instruments, Whitehall, PA) and electromechanical switches were used to provide manual control of the reinforcer. Lever presses and reinforcer deliveries were automatically recorded on the monitor and in a data file.

Procedure

Water deprivation condition. The rats were randomly divided into two groups: eight rats (evening group) were put on water deprivation at 20:00 and started training and testing at 20:00 on the next day; and the other eight rats (morning group) were put all water deprivation at 8:00 and started training and testing at 8:00 on the next day. If the animals had more than one day off from the experiment, they were given free access to water until about 24 hours before the next experimental session. All rats were weighed daily and approximately 85% of free-feeding weight was maintained. If a rat was weighed less than its 85% of free-feeding weight, it would be put on a break from the experiment until it regained its weight.

Preliminary training. The houselight was illuminated at the start of each session. All rats were autoshaped to pressing the lever for one day. They were then trained to perform reliably at pressing both the right and left levers to get one dipper of water on a variable-ratio 2 (VR2) schedule. This process ensured consistent responding on both levers. The rats were moved to the next phase after they had received at least 50 reinforcements in a single 30-min session.

Self-control task training. The houselight was illuminated at the start of the session. Four rats that were trained and tested at 8:00 in the morning and four rats that were trained

and tested at 20:00 in the evening were trained in the chamber, in which they had to choose between pressing the right lever, which resulted in a 5-second delay before an 8-second access to two dippers of water (large reward), and pressing the left lever, which resulted in an 2-second delay before a 3-second access to one dipper of water (small reward). The two dippers of water were given by the dipper going up for 4 seconds, quickly going down and then going up again for another 4 seconds. The other eight rats were trained in the chamber, in which pressing the right lever resulted in an 2-second delay before a 3-second access to one dipper of water, whereas pressing the left lever resulted in a 5-second delay before an 8-second access to two dippers of water. The purpose of this procedure was to ensure that the results were not due to the rats' preference to a certain orientation. After water delivery, two levers were retracted for 10 seconds. At least 50 choices had to be made by the rats in a single session and over 70 percent of the choices needed to be to the large reward before the delay prior to gradually increasing the large reward delay to 8 seconds and then to 10 seconds. The number of right and left lever pressings was recorded.

Testing. For each session, the number of long-delayed-reinforcer lever pressings (LP), the number of short-delayed-reinforcer lever pressings (SP), the number of large reinforcers, and the number of small reinforcers earned were recorded. The percentage of large-reward preference (LP/(LP+SP)) * 100) was calculated at the end of each session.

There were five test days in total and a three-day interval between each test day to reduce the possibility that the rats got used to the noise "blast" (see below), during which they were put back on Self-Control Task Training.

On the first test day, rats in the morning group were put on water deprivation during their dark cycle (8pm - 8am) the day before and rats in the evening group were put on water deprivation during their light cycle (8am - 8pm) the day before. The percentage of choices to the large reward was recorded to serve as the rats' baseline self-control.

On the second test day, four rats in the morning group and four rats in the evening group were randomly selected to be put on water and food deprivation for 12 hours during their dark cycle (from 8pm to 8am) the day before. At 8am, these eight rats received a random white noise blast (90 dB) for 10 seconds every minute, which lasted for 15 minutes (Muraven & Baumeister, 2000). Then two of the four rats in the morning group were returned into the home cage to consume 0.80 ml water by using syringe feeding and the other two rats in the morning group were returned into the home cage to consume 0.80 ml glucose drink (Gluco Shot, CVS, Saint Paul, MN). The volume of glucose drink administered was calculated based on the similar experiment on dogs (Miller et al., 2010).

A 2-minute delay between the feeding and the self-control task was included in order for the glucose to be metabolized (Betz, Gilboe, Yudilevich, & Drewes, 1973). Then the rats were put into the self-control task. The four rats in the evening group that were put on water and food deprivation were tested at 8 pm after receiving a random white noise and consuming either 0.80 ml water or glucose drink. The remaining eight rats were put on water deprivation for 12 hours during either their light cycle or dark cycle the day before. The food was weighed before and after the 12 hours and the mass of food eaten was recorded for each cage. The remaining eight rats followed the same procedure to test their self-control. All rats

were returned to the cage right after the task and had free access to the water. The percentage of choices to the large reward was recorded to serve as the rats' self-control in four conditions: (1) water deprivation + water condition, (2) water deprivation + glucose condition, (3) water & food deprivation + water condition or (4) water & food deprivation + glucose condition.

The rats that were on water deprivation on the second test day were put on water deprivation on the third test day, and on water and food deprivation on the fourth and fifth test days; at the same time, the rats that were on water & food deprivation on the second test day were put on water and food deprivation on the third test day and water deprivation on the fourth and fifth test days. The rats that consumed water on the second day consumed glucose drink on the third day and fourth day and water on the fifth day. The percentage of choices to the large reward in the four conditions on each test day was recorded to serve as their self-control.

Results

Analysis focused on the percentage of choices to the large but 10-second-delayed reward over the small but 2-second-delayed reward to examine (1) whether self-control was depleted by the noise blast and whether glucose reimbursed self-control depletion, (2) whether rats showed more self-control depletion and glucose had more replenishing effect when they were on food deprivation, and (3) whether rats showed more self-control depletion and glucose had more replenishing effect when they were more aware of food deprivation

(deprived during the dark cycle) compared to when they were less aware of food deprivation (deprived during the light cycle).

A repeated measures ANOVA was performed with mixed factors. Time served as the between subject factor and all other factors were within subjects. The LSD test was used to perform the post hoc analysis.

There was a significant difference ($F(2, 28) = 12.80$, $p < .001$***, $\eta^2 = .478$; see Figure 1) among the average baseline self-control, the average self-control depletion, and the average self-control reimbursement. After the noise blast, rats showed significantly less self-control (M= 53.39%, SD= 26.02%, $p < .001$***) compared to their baseline self-control (M= 66.22%, SD= 24.99%). After they were orally injected glucose, the rats' self-control (M= 61.05%, SD= 27.32%, $p = 0.010$**) was significantly improved; however, glucose did not bring rats' self-control back to baseline ($p = 0.043$*).

There was also a significant effect of food deprivation ($F(1, 14) = 12.92$, $p = .003$**, $\eta^2 = .480$, see Figure 2). When rats were on water and food deprivation, their self-control (M= 55.30%, SD= 25.37%) was significantly lower than when they were only on water deprivation (M= 65.14%, SD= 26.48%, $p = .003$**). The interaction of food deprivation and depletion was significant ($F(2, 28) = 6.627$, $p = .004$**, $\eta^2 = .321$; see Figure 2), which suggested that the effect of self-control depletion differed depending on whether the rats were put on a food deprivation or not. Food deprivation made the rats' self-control more depleted (M= 45.36%, SD= 22.73%) compared to that in no food deprivation condition (M= 61.43%, SD= 27.29%). Glucose consumption showed greater relative improvement in

self-control (*M*= 54.33%, *SD*= 25.34%) when the rats were on food deprivation compared to when they were not on food deprivation (*M*= 67.77%, *SD*= 28.36%). However, glucose did not bring rats' self-control closer to baseline when they were on food deprivation compared to when they were not.

The rats that were not put on food deprivation during the day consumed on average 9g/cage rat chow and the rats that were not put on food deprivation during the night consumed on average 20g/cage rat chow. The rats' self-control was trending toward a difference between whether they were tested at 8am or at 8pm ($F(1, 14) = 4.30$, $p = .057$, $\eta^2 = .235$; see Figure 3). The average self-control of rats tested at 8am was 77.54% (*SD*= 18.72%) at the baseline level, 62.51% (*SD*= 23.60%) when they were depleted by the noise blast, and 74.11% (*SD*= 17.77%) after they consumed the glucose drink. The average self-control of rats tested at 8pm was 54.90% (*SD*= 26.36%), 44.27% (*SD*= 24.28%) when they were depleted by the noise blast, and 47.99% (*SD*= 28.54%) after they consumed the glucose drink. The interactions of testing time and food deprivation ($F(1, 14) = .76$, $p = .397$, $\eta^2 = .052$), testing time and depletion ($F(2, 28) = 1.12$, $p = .317$, $\eta^2 = .079$), testing time, food deprivation and depletion ($F(2, 28) = .442$, $p = .647$, $\eta^2 = .031$) were not significant.

In the present study, rats demonstrated individual differences. Some rats showed consistently lower self-control compared to other rats. Several rats showed an increase in self-control when they were only put on water deprivation, but they showed self-control depletion when they were put on water & food deprivation (see Figure 4).

Discussion

This study examined an imposition theory proposed to reconcile the contradiction of self-control depletion and the replenishing effect of glucose in previous research, which states that (1) energy deprivation is the prerequisite condition; (2) self-awareness of the deprivation modulates the extent. Three hypotheses were proposed based on the theory. The result supported the first hypothesis that rats' self-control would be depleted and glucose consumption would reimburse self-control depletion, although glucose consumption did not bring the rats' self-control totally back to baseline.

The second hypothesis that rats would show more self-control depletion and a more replenishing effect of glucose if they were on food deprivation compared to if they were not on food deprivation was partially supported by the result. Figure 1 shows that rats did show more self-control depletion while they were on food deprivation, but glucose had similar replenishing effects in both conditions. Rats experiencing water & food deprivation were not brought as close to baseline after receiving glucose as when they were in water deprivation, perhaps because the level of rats' self-control was so much lower with food deprivation. The ways in which the results supported the first and second hypothesis indicated a limited replenishing effect of glucose, which largely depended on how depleted the rats were after being exposed to the noise blast.

One challenge of this model was that rats could not perform as complex cognitive tasks as humans do. Consider that the *delay of gratification* task often involves water or food as reward. The rats in the present study were always on water deprivation during the training and testing in order for them to perform on lever pressing. The restriction of water intake in

rats could result in depression of food intake (Strominger, 1947). Therefore, the rats were always being energy deprived to some level in the experiment. As a result, we introduced water & food deprivation to serve as the more deprived experimental group. We proposed that a more deprived condition would result in more self-control depletion and more glucose reimbursement. Nevertheless, the control group in this experiment cannot be deprivation-free and thus the result cannot fully conclude whether being energy deprived is the prerequisite condition.

At the same time, the individual differences demonstrated in rats may provide indirect evidence of whether energy deprivation is the prerequisite condition. Recall the individual differences demonstrated in rats. Some rats showed consistently lower self-control compared to other rats. This pattern is consistent with the individual difference in self-control found in humans as early as preschool (Mischel et al., 1989). Despite individual difference, most of the rats showed self-control depletion and all rats were brought closer to baseline after consuming glucose. From Figure 4, it is observed that several rats actually showed an increase in self-control when they were put on water deprivation, which was also consistent with some past studies, in which some participants showed an increase of glucose level while a drop was expected (Gailliot et al., 2007; Kurzban, 2010). However, in the current study, the rats whose self-control increased when they were on water deprivation showed self-control depletion when they were put on water & food deprivation (see Figure 4). When the rats were on water & food deprivation, the trend across baseline condition, depletion condition

and glucose condition was more consistent, which suggests that energy deprivation could be necessary to ensure that self-control depletion happens.

Compared to the rats that were tested at 8am, the rats that were tested at 8pm showed less self-control, which was a marginally significant difference. Therefore, one can argue that the rats that were more aware of the food deprivation (deprived during the dark cycle) had higher self-control compared to the rats there were less aware of the food deprivation (deprived during the light cycle), which showed the opposite trend as the third hypothesis predicted. Furthermore, it is interesting to note the effect of testing time on the difference of self-control depletion and glucose reimbursement between water deprivation group and water & food deprivation group. Although Figure 3 showed that testing at 8am did drop the rats' self-control more when they were exposed to the noise blast and glucose did increase the rats' self-control more when they were put on water & food deprivation, there was no statistical significance of the interaction of testing time, depletion condition and food deprivation.

As the rats did eat more rat chow during the dark cycle compared to the light cycle according to the amount of food measured for each rat, it is unlikely that their circadian rhythm was flipped because of their testing time. The opposite trend may be explained from several aspects. Past studies showed that testing mice during the light cycle induced a behavioral inhibition and a cognitive disruption, including less exploratory behaviors (Roedel et al., 2006). It is likely that if the rats withheld their behavior more during the light cycle, the rats that were tested at 8am (during light cycle) would be less impulsive. Therefore,

they would show more self-control in this experiment. Previous studies have also shown that long duration food deprivation (80hrs) was able to decrease rats' total sleep episodes (Borbély, 1977). Sleep deprivation may impair prefrontal cortex function, which is closely associated with cognitive functions (Kamphuis et al., 2017). In another study, sleep deprived rats pressed the lever more randomly and showed behavioral dis-inhibition, which possibly leads to impulsivity (Kamphuis et al., 2017).

In the present study, rats that were food deprived during their resting phase (the light cycle) may have been more likely to be sleep deprived, which might result in less self-control compared to the rats that were food deprived during the dark cycle. However, it is still unknown whether the negative effect of the self-awareness of the deprivation is masked by the effect of sleep deprivation or whether there is no effect of the self-awareness of the deprivation. Another problem with this explanation is that short-term food deprivation (8hrs) did not significantly change the sleeping states of rats (Borbély, 1977). Therefore, even if food deprivation induced sleep reduction, such an effect could be limited.

It is also a challenge to manipulate and test self-awareness in rats. Although rats' cognitive functions are demonstrated by their ability to learn, memorize and plan, their cognitive functions have limitations that makes them differ from human beings (such as recognizing themselves in mirror) (Gallup, 1982). Just as humans are more capable of reflecting upon their lives, they also exceed other animals in the capacity for self-control (Schmeichel & Vohs, 2009). Another key difference is that human subjects need to use their conscious effort to withhold eating if they are instructed to skip meals. Rats were passively

involved in food deprivation in this study. The lack of conscious effort and the limited cognitive function in rats may all contribute to the marginally significant effect of testing time in this study.

Several limitations in this study can be addressed in the future. The effect of food deprivation could be connected with the type of self-control tasks. Water, as the reward in this experiment, was closely associated with food intake, especially in rats. The restriction of water intake would result in depression of food intake and the restriction of food intake would result in depression of water intake (Strominger, 1947). How the water deprivation during the training and the water they drank during the test affected the results in this experiment was not addressed in this methodology. Therefore, future studies should explore other potential positive rewards to use in the *delay of gratification* task for rats. For example, increasing the amount of time of social interaction can be an effective positive reinforcer for rats (Douglas, Varlinskaya, & Spear, 2004). Humans and other primates could be proper subjects to replicate this study as well, as they are able to perform more complex cognitive tasks that do not necessarily involve food.

There are several improvements that can be made in the future research. The present study recorded the rats self-control during the intervals between each test day to make sure that the rats went back to their baseline. However, the performance of the rats on the test day could be influenced by factors such as the rats' estrous cycle. Future studies should test the self-control in each condition for multiple days and average several tests' result so that the performance of rats can be better measured. Further, the present studies aim to provide

behavioral analysis of the rats' self-control without distinguishing the underlying motivational and metabolic mechanism of the energy model of self-control. Despite what has been done in human studies, animal models can be used to examine the underlying mechanism in highly controlled experiments. Future studies might employ artificial sweetener to test whether the sweetness itself is enough to have a replenishing effect on self-control depletion in rats. With the successful establishment of this rat model, biological examination could also be applied to show the self-control depletion process and the underlying mechanism in rats.

In conclusion, the present study offered a novel animal model that has not been used in studying the strength model of self-control, providing insights into the possible ways of increasing self-control in humans and the potential effects of using reward containing glucose in animal training. Although the mechanism of self-control depletion and glucose reimbursement still remains an open question, the studies argued for the existence of self-control depletion and the replenishing effect of glucose under the energy depletion condition. Finally, the present study also offered an integrated explanation for why the contradiction of self-control depletion and the replenishing effect may exist in past research. The imposition theory was consistent with the trends shown in the results indicating that rats had significantly more self-control depletion when they were on food deprivation and that there was a marginally significant influence on the self-awareness of the deprivation. At the same time, (1) whether being energy deprived is the prerequisite condition and (2) whether self-awareness of the deprivation modulates the extent still requires further examination,

perhaps by using different methodologies and testing on different subjects to provide more direct and full support.

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Supportive Evidence	Food Deprivation Condition
Human subjects	
Baumeister et al. (1998, experiment 1)	Avoided eating for at least 3 hrs
Stucke and Baumeister (2006, experiment 1)	Avoided eating for at least 3 hrs
Gailliot et al. (2007, experiment 1 & 2)	Avoided eating for 3 hrs
Dewall et al. (2007, experiment 1)	Avoided eating for 3 hrs
Dvorak and Simons (2009)	Avoided eating for 3 hrs
Denson et al. (2010).	Avoided eating for at least 3 hrs
Hagger and Chatzisarantis (2013)	Avoided eating for 3 hrs
Carter and McCullough (2013)	Avoided eating for at least 3 hrs
Masicampo and Baumeister (2008)	Same author which suggests consistent methodology (Baumeister, 1998)
Gailliot et al. (2009)	Same authors which suggest consistent methodology (Gailliot et al., 2007)
Animal subjects	
Miller et al.(2010)	Withheld food for 4 hrs
Mayack and Naug (2015)	Food Deprivation for 6, 18, and 24 hours

Table 1. Food deprivation condition that was implemented by each experiment, which had experiment results that indicated self-control depletion and/or the replenishing effect of glucose.

Unsupportive Evidence	Pre-test Condition
Human subjects	
Lange et al. (2014)	Avoided eating for 1.5 hrs
Xu et al. (2014)	Avoided eating for 2 hrs
Lange and Eggert (2014, experiment 1)	Avoided eating for 1.5 hrs
Lange and Eggert (2014, experiment 2)	Avoided eating for 2 hrs
Kelly, Sünram-Lea and Crawford (2015)	Avoided eating for 2 hrs
Boyle et al. (2016)	Tested between 0700 - 1030 after an overnight fast
Animal subjects	
Miller (2013)	Withheld breakfast after an overnight fast
De Petrillo et al. (2015)	Never food deprived for testing
Parrish et al. (2016)	Did not deviate from the typical dietary routine

Table 2. Food deprivation condition that was implemented by each experiment, which had experiment results that did not indicate self-control depletion or the replenishing effect of glucose.

Mixed result with psychological effect involved	Pre-test Condition
Human subjects	
Schmeichel and Vohs (2009)	No food deprivation
Job et al. (2013, experiment 1 & 2)	Avoided eating for 2 hrs
Job et al. (2013, experiment 3)	No food deprivation
Hagger and Chatzisarantis (2013)	Avoided eating for 3 hrs

Table 3. Food deprivation condition that was implemented by the experiments, which indicated an interaction between the psychological effects and the replenishing effect of glucose.

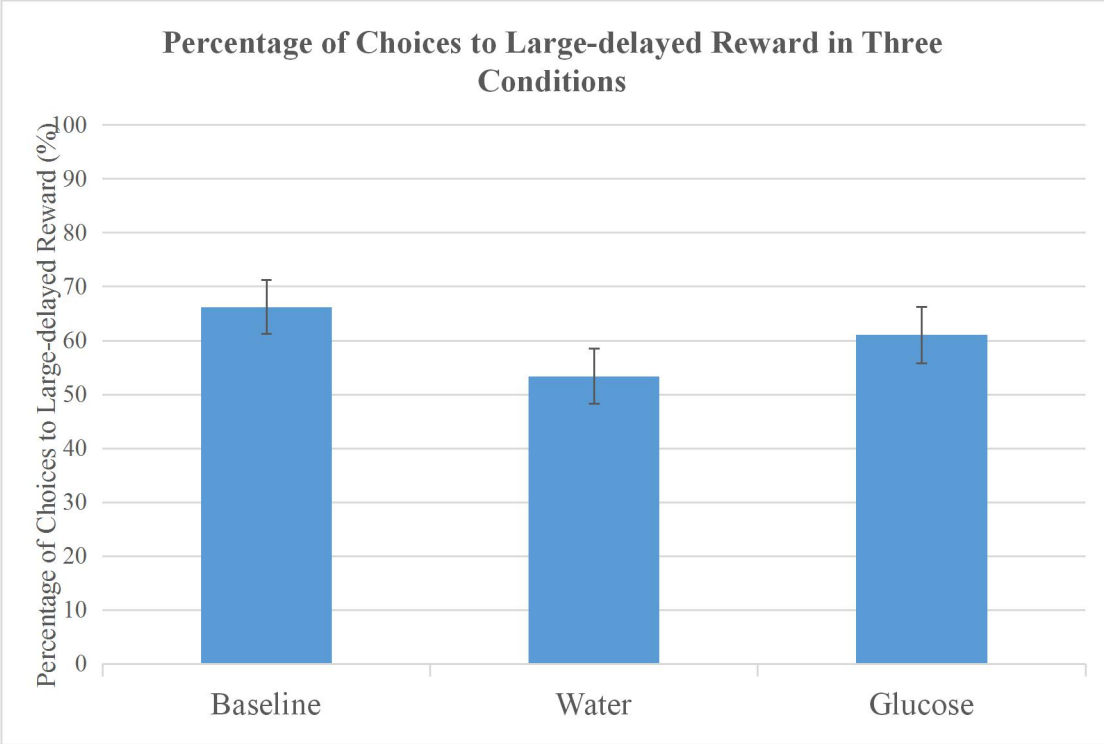

Figure 1. The average percentage of choices to the large-delayed reward in baseline condition, self-control depletion condition and glucose reimbursement condition. The error bars show standard errors.

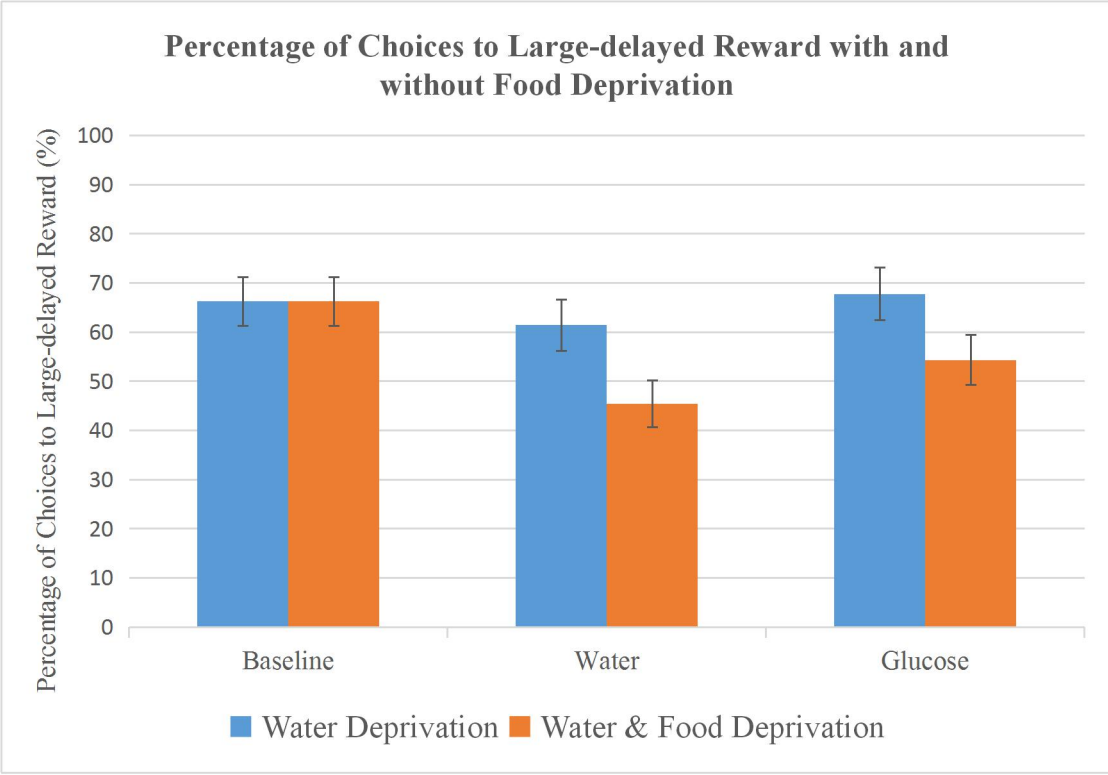

Figure 2. The average percentage of choices to the large-delayed reward when the rats were only water deprived and were given water or glucose and when the rats were water and food deprived and were given water or glucose. The error bars show standard errors.

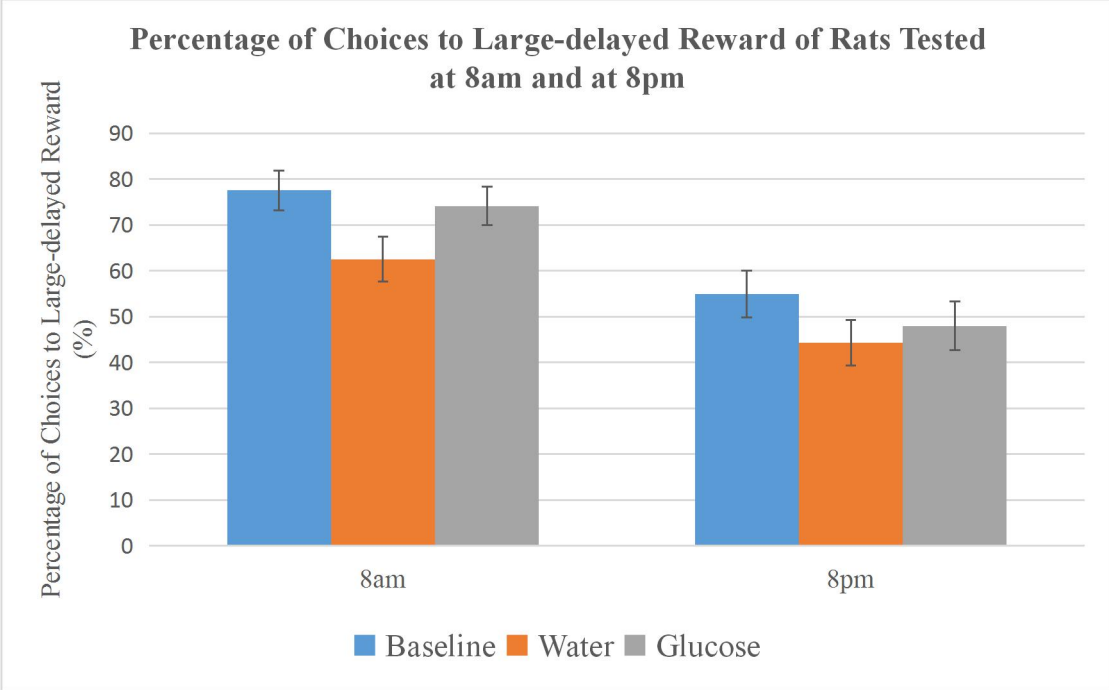

Figure 3. The average percentage of choices to the large-delayed reward between the rats that were tested at 8am and the rats that were tested at 8pm. The error bars show standard errors.

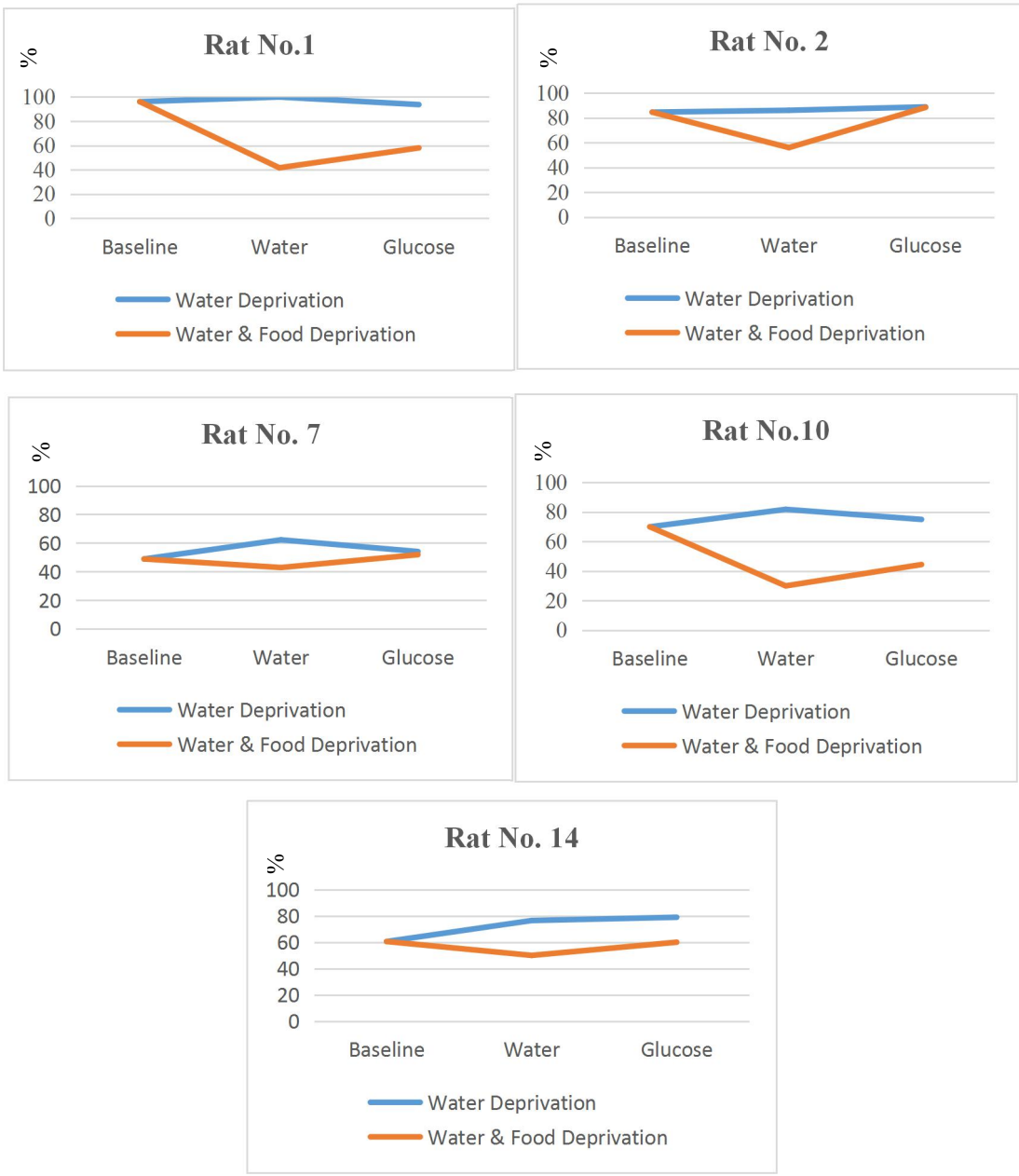

Figure 4. Rats showed an increase in self-control when they were put on water deprivation, but showed self-control depletion when they were put on water & food deprivation.

Appendix A

The Influence of Glucose Pre-feeding on Self-control in Rats

This study hoped to establish a new animal model by testing self-control in rats under four conditions: baseline, depletion, glucose and water. The goal is to study (1) whether the ability of self-control could be depleted and (2) whether glucose pre-feeding could increase self-control in rats. We explored the potential self-control depletion task by using differential-reinforcement-of-low-rate (DRL) schedule, a schedule that required subjects to withhold a response. The *delay of gratification* task was used to measure self-control and water was used as the reinforcer.

The baseline condition tested the self-control ability without a depletion task; the depletion condition tested the self-control ability after the rats performed on a depletion task; in the glucose condition, the rats were fed with glucose after the depletion task and then tested for self-control ability; in the water condition, the rats were fed with water after the depletion task and then tested for self-control ability. In this experiment, we proposed that after exerting self-control, rats would have less self-control in the subsequent task. We also proposed that glucose pre-feeding would be effective in increasing self-control in rats.

Method

Subject

Eight female naive Sprague-Dawley rats bred in-house at Macalester College served as subjects. They were all approximately 100 days old at the beginning of the experiment. The rats were allowed access to food *ad libitum* and were housed in same-sex groups of two in a

temperature- and humidity- controlled environment under a 12-h light/dark cycle (lights off at 8.00 P.M.). Before each experimental session, the rats were put on water deprivation for 24 to 36 hours. After each daily session, at least 20 minutes of free water access was provided for each rat in the home cage. On days when the experiment was not run, 30 minutes of free water access was provided. If the animals had more than one day off from the experiment, they were given free access to water until about 24 hours before the next experimental session. All rats were weighed daily and approximately 85% of free-feeding weight was maintained.

Apparatus

Ten Coulbourn Instruments Large Modular Test Cages (Lehigh Valley, PA) comprised the test chambers used in the experiment. Each chamber was equipped with light mounted in the upper portion of the center of the modular wall (Coulbourn Instruments), a feeder device, and a dipper (0.6 ml) (BioServ, Frenchtown, USA) where water was provided. In the depletion phase, the H21-09R nose-poke operandum (Coulbourn Instruments) was mounted in the lower left panel and the dipper was mounted in the lower right panel. The nose poke operandum had a one inch diameter entrance hole, where the rats could put their noses in. The detection of their noses was made by an invisible (940 nM) infrared photo beam across the opening. In the self-control phase, two retractable levers (Med-Associates) were mounted symmetrically in the lower panel and the dipper was mounted in the lower center panel. The reinforcer in the experiment was water.

A solid-state interfacing (Med-Associates), a computer, Med-PC IV software and electromechanical switches were used to provide manual control of the reinforcer. Lever presses and reinforcer deliveries were automatically recorded on the monitor.

Procedure

Preliminary training. The houselight was illuminated at the start of each session. All rats were autoshaped on pressing the lever for one day. They were then trained to perform reliably on pressing both the right and left levers to get one dipper of water on variable-ratio 2 (VR2). This ensures consistent responding on both levers. They were moved to the next phase after they had received at least 50 reinforcement in a single session.

Training. They were first put on self-control task training I for four days followed by depletion task training for two days. For each of the next five days, they were trained on self-control task training II for 30 minutes and depletion task training for 30 minutes.

Depletion training. During the depletion training, the nose-poke operandum was used. All rats were trained in chamber, in which the houselight was turned on and off every five minutes for 30 minutes. When the houselight was off, the rats were put on VR5 schedule, in which a dipper of water was given for the average of five responses. A response was putting the nose into the nose-poke operandum. When the houselight was illuminated, the rats were put on differential-reinforcement-of-low-rate (DRL) schedule. DRL is a schedule, under which a subject is required to withhold a response for a certain amount of time in order to get the reinforcement (Kirshenbaum, Brown, Hughes, & Doughty, 2008). It inhibits the subject's response and therefore needs the subjects to exert self-control over their behaviors, which

serves as a depletion task in this experiment. Depletion tasks have been shown to produce an impairment of performance in the subsequent task (Hagger, Wood, Stiff, & Chatzisarantis, 2010). The amount of time that the rats needed to withhold a nose-poking response started from 10s and increased to 20s over the seven days of training. At the end of the seven-day training, the rats got at least 15 reinforcements during the DRL schedule in a single depletion training session. The number of nose poking in VR-5 and DRL schedules was recorded.

Self-control task training I. The houselight was illuminated at the start of each session. Three of the eight rats were trained in chamber, in which they had to choose between pressing the right lever which resulted in an 8-second access to two dippers of water (large reward) and pressing the left lever which resulted in a 3-second access to one dipper of water (small reward). The two dippers of water were given by the dipper going up for 4 seconds, quickly going down and then going up again for another 4 seconds. The other five rats were trained in chamber, in which pressing the right lever resulted in a 3-second access to one dipper of water, whereas pressing the left lever resulted in an 8-second access to two dippers of water (Van Haaren et al., 1988). In this way, it made sure that the results were not due to the rats' preference to a certain orientation. After water delivery, two levers were retrieved for 10 seconds. At least 50 choices had to be made by the rats in a single session and over 70 percent of the choices needed to be the large reward before the rats could be put in self-control task training II. The number of right and left lever pressings was recorded.

Self-control task training II. The houselight was illuminated at the start of the session. The three rats, which had learned that the right lever resulted in two dippers of water, were

trained in chamber, in which they had to choose between pressing the right lever which resulted in a 6-second delay before an 8-second access to two dippers of water and pressing the left lever which resulted in an immediate 3-second access to one dipper of water. The other five rats were trained in chamber, in which pressing the right lever resulted in an immediate 3-second access to one dipper of water, whereas pressing the left lever resulted in a 6-second delay before an 8-second access to two dippers of water. After water delivery, two levers were retrieved for 10 seconds. On the first day of the training, the rats did not learn that one lever made them to wait for six seconds; instead, they wandered in the test cage in that six seconds and missed the reward. On the second day, all rats stopped responding to the lever related to the large reward and only responded to the lever that gave an immediate reward. Therefore, the program was changed so that the rats, instead of getting an immediate small reward, had to wait for two seconds. The program that the rats had to choose between waiting 6 seconds for an 8-second access to two dippers of water and waiting 2 seconds for a 3-second access to one dipper of water served as their self-control task. Afterwards, the rats' self-control was gradually consistent with what had been shown in previous study (Van Haaren et al. 1988). At least 50 choices had to be made by the rats in a single session before the rats could be put in the testing phase. The number of right and left lever pressings was recorded.

Testing. For each session, the number of long-delayed-reinforcer lever pressings (DP), the number of short-delayed-reinforcer lever pressings (IP) and the number of large reinforcers and the number of small reinforcers earned were recorded. The percentage of

large-reward preference (DP/(DP+IP)×100) was calculated at the end of each session. The preference on the last day of the training phase was recorded to serve as the baseline self-control.

Between each testing day, the rats were put on the depletion training schedule for 30 minutes and on the self-control task for 30 minutes for one day. In the depletion condition, all rats were first put on the depletion task, in which they were put on DRL-20s schedule for 15 minutes while the houselight was illuminated. Then they were put back into home cage for two minutes before being tested in the self-control task. The percentage of choices to the large reward was recorded to serve as the rats' self-control in the depletion condition.

In the water condition, the rats were first put on the depletion task. Then they were returned into the home cages to consume 0.50 ml water by using syringe feeding. A 2-minute delay between the feeding and the self-control task was included. Then they were put in the self-control task. The percentage of choices to the large reward was recorded to serve as the rats' self-control in the water condition.

In the glucose condition, all rats were put on the depletion task. Then they were given 0.50 ml of the glucose drink (Gluco Shot, CVS, Saint Paul, MN), which was calculated based on the similar experiment on dogs (Miller et al., 2010). A 2-minute delay between the feeding and the self-control task was included in order for the glucose to be metabolized (Betz, Gilboe, Yudilevich, & Drewes, 1973). Then they were put in the self-control task. The percentage of choices to the large reward was recorded to serve as the self-control in the glucose condition.

Results

Analyses focused on the percentage of choices to the large but 6-second-delayed reward over the small but 2-second-delayed reward under four different experimental conditions: baseline condition, depletion condition, water condition and glucose condition. One rat failed to complete the training phase and therefore it was excluded from all data. A repeated measures ANOVA test was performed to determine the significance of the difference among four different conditions. There was no significant effect, $F(1.561, 9.366) = 1.004$, $p = 0.382$, among conditions. However, when the rats were fed with glucose, their self-control (M= 91.67%, SD= 10.81%) was trending toward a difference compared to their baseline self-control (M= 83.48%, SD= 15.55%; see Figure A1). There was no significant difference of self-control between control and depletion conditions (M= 87.29%, SD= 17.45%) , control and water conditions (M= 85.67%, SD= 19.46%), or water and glucose conditions.

Discussion

This study examined both the depletion effect and the effect of glucose pre-feeding on self-control in rats. There was no significant difference among groups, which did not support the hypothesis that self-control would be depleted in rats and that glucose would reverse this depletion. After the DRL procedure, in which all rats in the experiment were forced to inhibit their lever-pressing behaviors, there was a slight increase of self-control ability in the following test. However, Figure A1 did show that glucose pre-feeding generated the highest self-control ability. Compared to the baseline self-control, the glucose condition showed an increase, that was trending toward a marginally significant difference, which indicates that

future studies are promising.

The reason that there was no depletion of self-control shown in rats after a 15-minute DRL-20s session may be due to several factors. First, the 15-minute depletion that we manipulated might not be enough to induce a depletion effect, because the experimenter observed that most of the impulsive responses happened at the the beginning of the self-control test but the rats regained their ability to exert self-control quickly. The DRL schedule that served as the depletion task in this experiment has not been used in previous studies for the same purpose. Therefore, the lack of depletion effect in rats might be due to the reason that the depletion task did not function. In this study, whether the depletion of self-control in rats can be induced by DRL schedule is still unknown and needs further examination.

A ceiling effect might result in the marginally significant difference between glucose and baseline conditions, in which glucose pre-feeding no longer had an effect on self-control because the baseline self-control was too high. This experiment required the rats to differentiate between waiting 6 second for an 8-second access to two dippers of water and waiting 2 second for a 3-second access to one dipper of water. Rats have been shown to have good self-control in experiment, in which most of the female rats and all of the male rats chose a larger reinforcer delayed up to 36.0 seconds over a small reinforcer delayed for 6.0 seconds in more than 90% of the trials (Van Haaren et al., 1998). Therefore, a 6-second delay for a larger reinforcer in this experiment might be so short that it was easy for the rats to choose to wait, which resulted in an already high level of self-control without glucose

pre-feeding. Further studies should increase the delay before the delivery of a large reward.

In conclusion, although the difference was not significant, the pattern shown between baseline condition and glucose condition in Figure A1 was consistent with the pattern that we proposed in the hypothesis. However, the rats showed better self-control after the depletion task, which was not expected. The results aligned with the replenishing effect of glucose on self-control that has been shown in previous studies (Miller et al. 2010). This study offered a new animal model that can be used to further examine self-control depletion and the replenishing effect of glucose.

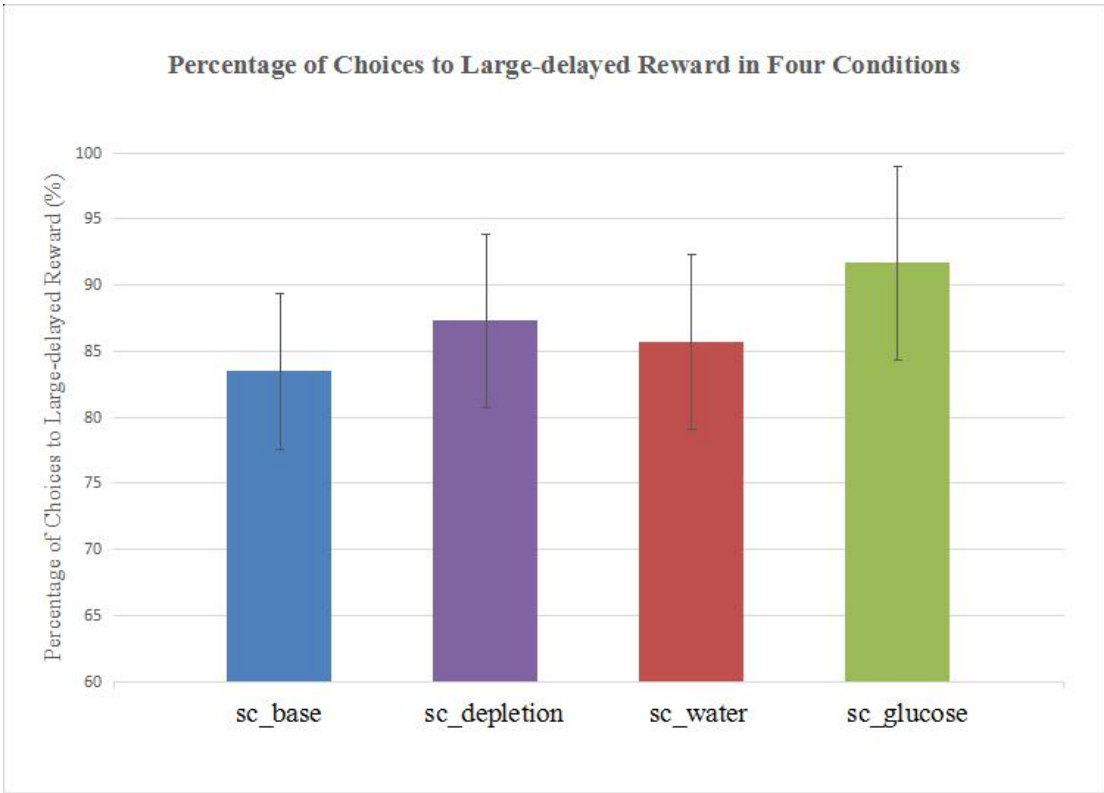

Figure A1. The average percentage of choices to the large-delayed reward in baseline, depletion, water and glucose conditions. The error bars show standard errors.