Influence of a High-Fat Diet on Delay Discounting, Food Reinforcement, and Eating Behaviors
in Sedentary and Endurance Trained Men

Olivia Frances Privitera

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Brenda M. Davy, Committee Chair
Madlyn Frisard
Jeff Stein

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ABSTRACT

People make food choices based upon the motivation to consume foods that are reinforcing compared to alternatives that may be available.[1] Delay discounting (DD) is a measure used to assess impulsivity, quantifying how people make decisions based on time to receive and amount of the choice presented.[2,3] The food purchase task (FPT) assesses the demand for a food and how reinforcing this item is at various prices.[4] Using a controlled feeding study design, 10 males (n=7 sedentary, n=10 endurance trained) consumed an iso-caloric, standard diet (55% carbohydrate, 30% fat, and 15% protein) for 10 days, followed by a high-fat diet (55% fat, 30% carbohydrate, 15% protein) for 5 days. DD, FPT, and Three Factor Eating Questionnaire (TFEQ) were assessed at three time points: baseline, after the standard diet/before high-fat diet, and after the high-fat diet. Discounting rates were significantly different at baseline between sedentary and endurance trained males, with the sedentary males having higher discounting rates (mean difference 1.43, $p=.037$). Discounting rates for the whole sample significantly decreased between baseline (time 1) and post-STD diet/before HFD (time 2), between time 2 and after the HFD (time 3), and between time 1 and time 3 (all indicated by $p<0.05$). No group differences were noted over time for demand elasticity, intensity, or TFEQ measures (all indicated by $p<0.05$). Results could be used to advance the understanding of factors that influence impulsive and unhealthy eating behaviors and inform the development of interventions that use reinforcers to positively influence eating behaviors.

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GENERAL AUDIENCE ABSTRACT

Choice is a fundamental part of life, and people make decisions based on a variety of different factors, such as the amount of effort required, perceived benefits and risks of the choice, what other options are available, and what resources the person has available to them (e.g., time, money). Many dietary and lifestyle choices are unhealthy, such as choosing to consume fast food in excess or to not engage in exercise. About 2/3 of Americans are overweight, and 1/3 are obese, and about 1 in 5 of American adults meet the guidelines recommended by the Centers for Disease Control of engaging in at least 150 minutes of moderate physical activity or 75 minutes of vigorous physical activity per week. Understanding the factors that influence unhealthy eating and lack of physical activity is crucial in order to develop effective programs that focus on changing these behaviors, as weight-loss or physical activity programs often require people to delay the immediate gratification of food in order to achieve optimal health outcomes. The present study investigates how a diet high in fat and exercise habits influence how people value rewards and make decisions. Delayed discounting is a tool used to determine much a person is influenced by immediate gratification of a reward versus waiting for a larger reward of greater worth that is available in the future. The food purchase task is used to quantify the reinforcing value of a food item by determining how much of a favorite snack food a person would purchase by depending on the price. Lastly, eating habits such as dietary restraint or loss of control are quantified by a questionnaire. Results could improve the understanding of factors that influence

unhealthy decisions and support the creation of programs that aim to improve how people view

and value future health outcomes.

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CHAPTER 1: INTRODUCTION

Prevalence of Obesity

The population of overweight and obese individuals in the United States is increasing, and accounts for two-thirds of the people in the United States, and more than one third of adults are obese.[1] Obesity is a major public health concern, and it does not result from a single influencing factor, but from multiple contributing factors such as genetics, behavior, and environmental factors.[2] It is difficult to treat obesity once it has developed since it often comes with comorbidities, such as type 2 diabetes and heart disease.[1] Obesity can result by consuming excess energy, meaning a person consumes more energy than he/she expends.[3,4]

Along with the growing obesity epidemic in the United States, about 1 in 5 adults meet the recommendation for physical activity provided by the Center for Disease Control, which states that adults should participate in 150 minutes of moderate or 75 minutes of vigorous physical activity per week.[5,6] A sedentary lifestyle is a risk factor for obesity and the comorbidities of obesity. In addition, lack of physical activity is associated with type 2 diabetes mellitus, cardiovascular disease, breast and colon cancer, hypertension, osteoporosis and osteopenia, and depression.[7] In order to create effective interventions to prevent and treat the growing obesity population, it is imperative to understand the intrinsic and extrinsic motivators that influence unhealthy eating behaviors.

Behavioral Economics

Behavioral economics studies how people make decisions in situations where there are a limited number of alternative choices.[8] The behavioral choice theory (also called the behavioral economic theory) defined by Epstein et al. is used to understand why people make choices depending on their resources (e.g., time and money) in an environment where variable

constraints, such as effort required, cost of product, distance to allocate product, etc., exist and are highly influencing when making a decision.[3] Related to food and activity choices, behavioral economics is used to understand how and why people make particular food choices depending on cost, alternatives available, and reinforcement value.[9]

The current environment in which people are immersed is often referred to as "obesogenic," and is created by Western societies.[10] It is defined by Martin and Davidson as, "low cost, energy-dense, highly-palatable, foods and beverages, and an abundance of external cues that keeps thoughts of these foods and beverages almost constantly in mind," and this environment, "overwhelms the physiological controls of energy-regulation."[10] The mechanism to understanding how this occurs is not clearly defined, as energy intake-regulation involves many factors, such as the cognitive processes involved with behavioral control and inhibition, which can be measured by tasks that assess impulsivity (described below).[10] Using the behavioral economic approach to assess food-related decisions is important in understanding who is at risk for overconsumption of calories and weight gain, and how these behaviors can be moderated by inventions that are designed to target these cognitive functions.

Delayed Discounting (DD)

DD is a measure used to determine the degree at which a person is driven by the immediate gratification of a small reward versus how likely they are to wait for a delayed reward of greater value.[3,11] DD is described as preferring smaller rewards that are available immediately over larger rewards that are available after a delay.[3] The value of a reward has been shown to decrease as a function of delay, and in the literature, DD is also referred to as present consumption bias, temporal discounting, time discounting, and delay of gratification.[12,13] DD is used in laboratories and clinical settings as a theoretical approach to assess impulsivity in the

context of decision making. It reflects a person's ability to self-regulate the intake of palatable foods in situations of non-homeostatic hunger, food cravings, and other sensory properties linked to consumption of tasty foods.[2,13]

In most research settings, DD is measured using a computerized choice-task using, where there is an immediate, smaller reward and a larger, delayed reward presented on opposite sides of the screen.[14] Once an option is chosen, the immediate option adjusts and gets larger or smaller, depending on the option the subject chose.[14] For example, suppose in the first choice task, a subject choses the larger, delayed option of $1000 vs. $500 available now. In the following choice task, the immediate option will titrate up to a larger amount, and the choice presented will be $1000 dollars after a delay vs. $625 available now.[14] The majority of the research studies measure DD using computerized choice tasks of hypothetical food, money, or activity rewards. A few older research studies have administered the DD task using index cards, and rewards are titrated in a similar way as in the computerized choice task. Johnson and Bickel and Reynolds et al. demonstrated that hypothetical and real amounts of monetary rewards are discounted comparably, and this concept is largely accepted by researchers.[15,16]

High DD rates indicate that a person more steeply discounts the value of the delayed reward, prefers the immediate reward more often, and is more impulsive. Low DD rates indicate that a person does not discount the value of the delayed reward as steeply, i.e. chooses more delayed rewards, and is less impulsive. Discounting rates are calculated by Mazur's (1987) hyperbolic free parameter k, which is calculated by the function V=A/1+kD, where V represents the subjective value of the delayed reward, A is the amount of the delayed reward, D is the delay, and k is the parameter that captures how steeply the reward decreases in value as the delay period increases.[17,18] The subjective value (V) is also referred to as the indifference point, and it is

determined by the point where the subject is indifferent between the immediate and delayed choice for a specific delay period and where the subject switches from choosing the larger, later reward to the smaller, sooner reward.[18]

Studies have found that discounting rates remain relatively stable over time.[19-21] When DD was tested one week apart in two studies, one using college students as the participants group and another using smokers vs. non-smokers, discovered that k values remained stable over time, evidenced by strong correlations ranging from .71 to .90 in the first study, and .55-.90 in the second study, respectively.[20,21] Another study investigated k values over a year period in college students, assessing DD at 3 different time points (an initial session, then five weeks later, then after a year from the second session) reported that discounting rates were relatively stable overtime.[19]

DD is also explained as an intertemporal choice problem, meaning the benefits and costs occur at different time points, either immediately or in the future.[12] For example, a person may choose to eat an unhealthy snack food now, like potato chips, where the pleasant sensory reward is immediate, but the cost of this behavior may be negative health effects in the future, such as heart disease or obesity.[12] Preference for immediate consumption (i.e. present consumption bias) results when a person places more weight on hedonic utility, meaning a person consumes a particular food item to satisfy a sensory (taste, smell, texture), emotional, or social need.[12] Hedonic eating is also referred to as reward-driven hunger, and is different from homeostatic eating in which the homeostatic system in the body and brain has control over energy balance and intake.[22] When a person places more weight on health utility, he/she considers the health benefits/consequences of the food greater than the sheer pleasure of consuming the food.[12]

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Related to food consumption, obese people may engage in unhealthy food-related behaviors, such as overconsumption, while discounting the possible future effects of this behavior, such as weight gain, obesity, future health problems, and increased medical expenses.[23] It has been hypothesized that high DD rates are associated with being overweight or obese, and a factor which may explain why people do not respond well to weight loss interventions.[13]

Relative Reinforcing Value (RRV) of Food

Food options are chosen based on the reinforcing value of food, which is defined by Epstein et al. as, "the motivation to obtain food, or how hard someone will work to obtain food."[3] Humans are creatures of habit and engage in activities that are satisfying, or in other words, reinforcing. As people continue to choose activities that are satisfying, they become more motivated to engage in this behavior, whether it is one that is healthy or unhealthy. This is often the case with gamblers, people with drug addictions, and people who consume excess calories.[3]

When varying amounts of a choice, or two different choices are offered at the same time, it is referred in the literature as assessing the reinforcing value of the commodities that are offered.[3] The reinforcing value can be assessed by the amount of effort a person is willing give to

allocate one food or another given two options, such as a healthy vs. unhealthy one, or between a food option and an activity. Realistically, reinforcers, such as a tasty food option vs. another commodity, are not accessible in isolation. Choice to consume one food item over another option depends on many factors, such as how much the person values the other option available, or how much the food costs, and that is how the RRV of food and DD relate.[3] DD varies from RRV because DD involves time to wait for an alternative and an intertemporal choice problem, where RRV involves how persistent a person is to work for a reward, and does not involve an intertemporal choice problem.[3] They are similar in that they both involve choosing between alternatives, and research has found that the RRV of food and DD can interact to predict energy intake.[3]

More specifically, the RRV of food is related to a person's sensitivity to food reward, which refers to how motivated a person is to eat because of the sensory pleasure and desirable effects associated with eating a particular food item, i.e. the smell of a cookie fresh out of the oven.[24] Past research reported a correlation between food reward sensitivity and stronger food cravings, higher body weight in adults and children, preference of palatable foods that are sweet and fat-dense, and greater energy intake in laboratory-based eating studies.[24] In addition, sensitivity to food reward was reported to be a risk factor for overconsumption, weight gain, and obesity. In addition, higher sensitivity to food reward and higher RRV of palatable foods were negatively correlated with poorer inhibitory control, indicating less ability to delay gratification and higher discounting rates.[24]

Price of Food and the Food Purchase Task

As described earlier, behavioral economics studies how people make decisions in the presence of alternatives. The demand curve shows the degree at which consumption of a

commodity decreases as the price increases and provides an index of the RRV of food.[25] The shape of the demand curve gives insight to the reinforcing value of the commodity.[25] Someone who finds the commodity very reinforcing will purchase the product at higher prices than the person who find the product less reinforcing.[25] The food purchase task (FPT) is used in the present study to measure the demand and reinforcing value of a favorite snack food.[25]

More specifically, the FPT creates a demand curve for each participant and provides a measure of demand intensity and demand elasticity of their preferred snack food.[25] Demand intensity measures how much a person would consume of the commodity if there was no price (i.e., free).[25] Demand elasticity measures the change in the amount of the commodity that is purchased as the price of that commodity increases.[12,25] The demand elasticity is also referred to as a the slope of the demand curve.[12] Other measures of the demand curve include: O_{max}, the price at which the person will spend the most on the commodity, P_{max}, the last price a person will purchase the commodity at before becoming sensitive to the price (i.e., elastic), and breakpoint, which is the price where no purchases of the commodity are made.[25] In addition, studies have grouped the measures of the demand curve into two categories of amplitude and persistence, where amplitude includes intensity, and persistence includes elasticity, breakpoint, O_{max} and P_{max}, and quantifies the relationship between price and purchases.[25]

The equation used to determine demand elasticity and intensity used in the present study is an exponential version of the behavioral economic demand model originally proposed by Hursh and Silberg.[26] This equation, $Q = Q_0 * 10^{k(e^{\wedge - \alpha Q_0 C - 1})}$ is used so that untransformed consumption values can fit the equation.[27] This is necessary as often times many participants respond with no consumption to questions in the FPT (i.e., zero purchases of their favorite snack food was made at a specific price). The original behavioral economic demand model requires

log-transforming consumption values and responses of no consumption (or zero purchases) would have to be omitted as they cannot be log transformed.[27] Therefore, this equation was utilized in the present study to treat zero consumption values so that this data can be included in the analyses.[27]

If a person finds a food item highly reinforcing, then they will theoretically purchase more of this food item vs. a person who does not find this food reinforcing. Greater elasticity, or very elastic, means that a person is more sensitive to a change in price of the commodity.[12] Elasticity increases when a shift in the food demand decreases due to an increase in price.[12] In contrast, inelastic reflects a person who is highly reinforced by a commodity and purchases more of the commodity at a higher price, meaning they are less sensitive to an increase in price of the commodity, and will continue to purchase the commodity as the price increases up to a point.[12]

Eating Behaviors

The Three-Factor Eating Questionnaire (TFEQ) measures three factors of human eating behavior: cognitive restraint (Factor I), disinhibition (Factor II), and perceived hunger (Factor III).[28] It is composed of 51 questions, including true/false and 4-point scale questions, where participants respond on how likely the question represents their behavior.

Cognitive restraint (Factor I) is defined as a person's conscious and mindful effort to prevent weight gain or promote weight loss by restricting his/her food intake.[29] Disinhibition (Factor II) is defined as how susceptible a person is to eat in response to a stimuli or the tendency to overeat in various circumstances, such as eating in an emotional state, eating in response to stress, or eating when a person is presented with many tasty foods.[28,29] Factor III is perceived hunger, and is defined as the susceptibility to eat in response to physiological symptoms that drive a person's need for food.[29]

Each of the three constructs of the TFEQ are scored independently of each other but are related. Research has reported that retrained eaters, when depressed, gained weight, while in contrast, unrestrained eaters lost weight when depressed.[28] Studies have also determined that dietary restraint is negatively correlated with energy and dietary fat intake, and that dietary restraint is a predictor of weight loss.[30,31] This is logical in that as a person restricts their dietary intake more, the less they will eat, and lower energy intake will lead to weight loss. Although, other studies reported that higher restraint was associated with higher BMI and body fat in normal weight men and women.[32] Overall, there is there is inconclusive evidence to determine whether restraint influences weight gain or loss, as results from studies are conflicting. One study reported that restraint moderated the effects of weight gain when women exhibited high disinhibition scores, as women who had high restraint and high disinhibition gained significantly more weight than women who had low restraint but high disinhibition scores in a retrospective study comparing body weight changes over six-time intervals.[33] Therefore, the effect of restraint on weight status may depend on disinhibition.[33]

Clinical research has investigated the relationship between the three factors of the TFEQ, body weight, weight gain, and food preferences. The TFEQ was tested for validity using obese women who reported binge eating, and it was determined that binge eating was highly correlated with high disinhibition and perceived hunger scores.[28] In addition, it has been reported that disinhibition can predict weight fluctuations.[28] In particular, studies by Epstein et al. and Carr et al. determined that high food reinforcement, disinhibition, and impulsivity are all positively correlated with a high BMI.[34,35]

Hays and Roberts reported positive correlations between high disinhibition scores and weight gain, high BMI, and hedonic food cues (eating in response for pleasure, rather than

physiological hunger).[29] In addition, they reported that weight gain and obesity in women ages 55-65 correlated most with a high disinhibition score on the TFEQ.[29] Lastly, Hays and Robert determined that habitual disinhibition, or the susceptibility to overeat in response to events that occur on a regular basis, may be the most important predictor for weight gain and BMI in women, rather than situational and emotional disinhibition, since they found these two subsets of disinhibition predicted weight gain and BMI less frequently.[29]

Along with determining that disinhibition and susceptibility to hunger are positivity correlated to BMI and body fat, Provencher et al. reported a positive relationship between higher subcutaneous adipose tissue in women and higher rigid restraint scores, which is defined as taking an all-or-nothing approach to dieting.[30] Some studies have also reported that restraint and disinhibition scores are lower in men compared to women.[29,30,36]

Studies have also investigated TFEQ measures over time. One study investigate how eating behaviors changed over a six-year period reported an increase in restraint scores over time in men, specifically restraining intake of fattening foods.[36] Reasoning behind this increase in restraint in men was hypothesized that as age increased, weight status became a larger concern possibility of aged-related diseases, such as cardiovascular disease.[36]

Another study investigated if a six-month exercise intervention affected eating behaviors.[36,37] It was reported that men with higher initial cognitive restraint scores maintained their weight throughout the course of the study, and men with lower initial restraint scores increased their weight and waist circumference over time.[37] In addition, this study reported that cognitive restraint, disinhibition, and appetite scores did not change from baseline to following the 6-month exercise intervention.[37]   Check citations

Brain Function and DD, Eating Behaviors, and Exercise

DD, food cues, exercise/physical activity, and eating behaviors measured by the TFEQ all have commonalities in terms of what neural processes and areas are activated. DD involves decision making and placing subjective values on rewards, and the prefrontal cortex (PFC) plays an important when working towards goals and determining the benefits and consequences of decisions.[23,24,38]

DD is often discussed in the context of inhibitory control, which is an interaction of the impulsive and executive systems of the brain.[38] Executive structures of the brain include the PFC, and specific areas within the PFC, such as the orbitofrontal cortex (OFC).[38,39] Other structures involved with executive control and response inhibition include the superior frontal gyrus, middle frontal gyrus, inferior frontal gyrus, and parietal cortex, and anterior insula.[40,41] Studies have linked reduced activity in the executive regions of the brain with obesity, and have reported that people with higher BMIs are more likely to have more structural brain abnormalities in these areas.[41,42]

Regions of the brain that are part of the impulsive system are the amygdala, nucleus acumens, and ventral pallidum.[38] Literature also groups other structures of limbic system with the impulsive system, such as the hippocampus, thalamus, hypothalamus, and more, which are involved with emotional processing and memory.[43] It is hypothesized that when making a decision, the executive and impulsive systems compete, and when one is more hyperactive than the other, addiction and other adaptive decision making can occur, and this has been termed the competing neurobehavioral decision systems hypothesis.[38,39]

In a meta-analysis that explored how DD and working memory affected cognitive function (utilizing methods of blood oxygen level-dependent (BOLD) and functional magnetic resonance imaging (fMRI) methods), DD was reported to engage limbic and neocortical

structures, in particular the striatum, insula, cingulate, and portions of the frontal lobe.[39] In addition, results concluded that the lateral PFC is active during decision making and considering the benefits and costs of alternatives.[39] In terms of the competing neurobehavioral decision systems hypothesis, decision making is impaired when either the of the systems (impulsive vs. executive) are more or less active, specifically when the prefrontal cortex is hypoactive, therefore the impulsive system has more influence in decision making.[39] This is important to recognize since when a person is immersed in an obesogenic environment, which can "overwhelm" physiological controls, the brain must be able to regulate the immediate gratification of energy-dense, palatable food options.[2,38,44]

A specific region of the PFC called the orbitofrontal cortex (OFC) has been linked to economic choice and decision making.[45] In particular, the OFC, "receives input from visual, somatosensory, olfactory, gustatory regions, limbic regions, and from the dorsal raphe," and "integrates these signals to create a subjective value for difference choices".[45] This the location where decisions are thought to be made.[45] Goal-directed behavior was reported to be impaired when lesions were present in the OFC and amygdala, but not when lesions were found in the lateral PFC, ventromedial PFC, or hippocampus.[45]

In terms of how exercise effects areas of the brain, studies have investigated how reward and appetite areas of the brain respond when exposed to high-calorie food cues (images of food items), and how physical activity may influence this response.[46,47] Key areas of the brain involved in appetite and reward were the amygdala, insula, and OFC.[47] Results reported that usual physical activity was associated with decreased responsiveness (indicated by less neuronal response) in the insula and post central gyrus when subjects were exposed to high caloric food cues following the consumption of a glucose beverage.[46] Participants who exhibited more

sedentary behaviors displayed higher brain response in these areas when exposed to these foods cues following the consumption of the glucose drink.[46] Another study found similar results, reporting that greater engagement in usual PA was associated with less activation in the OFC and left anterior insula in response to high-calorie food cues.[47] Reduced activation in these regions was associated with less self-reported desire and preference to consume these high-calorie foods.[47]

In addition, Evero et al. investigated neuronal activity when exposed to high or low calorie foods following 60-min of aerobic exercise performed at $83\pm1.0\%$ maximal heart rate or after 60 minutes of no exercise.[48] Results indicated that following exercise (vs. no acute exercise bout), neuronal activity decreased in regions of the brain involved with food reward (bilateral insula, right putamen, right rolandic operculum, and right inferior OFC), in response to high-calories foods vs. controls, and in response to low-calorie foods vs. controls.[48] Cornier et al. reported that the insula played a role in exercise-induced weight loss and weight loss maintenance in a 6-month exercise intervention study that investigated how exercise affects response to visual food cues in certain regions of the brain.[37]

It is important to note that DD, which involves an intertemporal choice, and the food purchase task, require a person to make a decision and place values on immediate and delayed rewards. Studies utilizing fMRI reported that DD tasks and exercise activate similar executive regions of the brain that food rewards/cues do, as evidenced by the research studies discussed above. Although the activation of brain regions is not investigated in the present study, the potential influence of exercise in moderating executive regions, specifically the PFC, OFC, and insula, is of interest and may be relevant to our results.[37]

Clinical Findings of Delayed Discounting and RRV, TFEQ, and Physical Activity

According to a review by Barlow et al., DD varies largely among individuals, and tends to be higher for adolescents, people of lower socioeconomic status (SES), and people of lower educational status who are also at a higher risk for obesity.[13] Additional research has found that people who are drug-dependent, have substance abuse problems (involving opioids, cocaine, or alcohol)[49], have a gambling problem[50], smoke cigarettes[51], and have a psychiatric condition[52] also demonstrate a greater preference for immediate rewards, therefore discounting the value of future rewards more than control groups. The majority of research in this area has used a cross-sectional design, but there have been some longitudinal studies that have investigated how physical activity and diet correlate with DD in rats and humans.

Several cross-sectional studies have investigated correlations between BMI and DD. Epstein et al. determined that higher BMI could be predicted if a participant was highly reinforced by high-energy dense foods and also discounted hypothetical, monetary delayed rewards more steeply.[53] The opposite was found to be significant as well (low BMI could be predicted for low DD values and reinforced by low energy dense foods.)[53] Participants who had high discounting rates generally had a BMI that was 3 units higher than participants who had low discounting rates. In addition, Epstein el al. reported that subjects who were more impulsive and found high energy dense foods highly reinforcing (high DD and high RRV of food) had a BMI that was 4 units higher than those who were less impulsive (low DD) and found high-energy dense foods less reinforcing.[53] Age, minority status, and TFEQ disinhibition or restraint did not significantly interact with high or low energy dense foods or DD to predict BMI, suggesting that increased BMI was independent of these factors in this sample of women.[53]

Similar to Epstein et al., Weller et al. reported that women who were obese (indicated by BMI) also had high DD values, suggesting that obese women discount the value of larger,

delayed monetary rewards more than normal weight women.[11,53] Weller et al. also concluded that differences in monetary DD rates between normal weight and obese women were not attributed to differences in age, income, or IQ.[11] Lastly, monetary DD values of normal weight women were comparable to normal weight and obese men in this particular study population.[11]

In contrast to Weller et al., Rasmussen et al. did not find a relationship between BMI and monetary or food DD or probability discounting (PD).[18] It was suggested that this could be due to the fact that Weller et al. used monetary values and delay periods that were much greater (up to $50,000 and many year delay periods) than in Rasmussen et al. ($10 and up to 1 year delay).[18]

Even though Rasmussen et al. did not find any relationship between DD and BMI, the authors determined that percent body fat (PBF) was a significant predictor of DD values for food DD.[18] This indicates that subjects who had a higher PBF made more impulsive food-related decisions compared to subjects who had a significantly lower PBF.[18] Lastly, Rasmussen et al. reported no correlation between subjective hunger measured on a 0-100 scale (0 meaning not hungry at all), hours since last meal or snack, and rates of discounting for food or money.[18]

Nederkoorn et al. did not find any significant differences between monetary DD tasks in obese and normal weight women (classified using BMI).[54] It has been proposed that the differences in findings between Nederkoorn et al. and Weller et al. may be due to differences in income in the normal weight and obese women in Nederkoorn's study, since this characteristic was not measured.[11,54]

Another study that investigated correlations between BMI and DD rates contained a larger sample size (n=100) and both males and females.[55] Jarmolowicz et al. discovered that regardless of sex, age, income, and education level, DD values were positively correlated with BMI, reporting that overweight/obese individuals exhibited higher DD rates than normal weight

individuals.[55] In addition, people who exhibited more depressive symptoms and who engaged in more self-reported fun-seeking behaviors also showed higher DD values.[55]

Researchers have investigated how the RRV and sensitivity to food reward interact with DD values, and how this interaction might be able to predict energy intake. The Power of Food Scale was used in two studies to investigate how motivated women were to consume highly palatable food in the absence of homeostatic hunger.[4,24] Appelhans et al. reported that household income levels and BMI in women were not significantly related to DD or food reward sensitivity.[24] Appelhans et al. also discovered that among overweight/obese women who were very sensitive to the reward properties of food (high food reinforcement, i.e., motivated to eat by the hedonic pleasure of consumption) and who discounted future rewards more greatly (high DD) consumed more palatable food in the absence of homeostatic hunger.[24] There was no association between consumption of palatable food and food reward sensitivity when overweight/obese women were less impulsive, indicated by low DD values.[24] Ely et al. used similar methods as Appelhans et al., but only normal weight women were studied. Ely et al. determined that the Power of Food Scale and DD did not significantly interact to predict palatable food intake in normal weight women.[4]

Rollins et al. investigated how DD and the RRV of food related to energy consumption during an ad-libitum eating task in non-obese women (BMI <30).[23] Results showed that women who had a high RRV of food and who also demonstrated greater discounting of delayed rewards on the DD tasks consumed more energy during the ad-libitum eating task than women who had a high RRV of food and who discounted delayed rewards less (low DD values).[23]

There has been minimal research that has investigated the relationship between the TFEQ measures and DD. Yeomans et al. reported that women who scored higher on the disinhibition

section of the TFEQ (TFEQ-D) were more impulsive, indicating higher DD values.[56] Additional

analyses explored how BMI correlated to the relationship between TFEQ-D and DD, and

discovered that BMI did not impact the results, suggesting that the differences between the low

and high disinhibition and DD cannot be attributed to BMI status.[56]

Additional research has investigated how food demand (measured by elasticity and

intensity), DD, BMI, and dietary restraint interact. Reslan et al. discovered that participants who

were more impulsive (classified by higher *k* values) were more price sensitive, displaying greater

demand elasticity on the demand curve.[57] Also, Reslan et al. reported that the demand for a high-

fat/high-sugar food item was more inelastic, meaning that participants were less sensitive to

changes in price, for overweight subjects than for non-overweight participants, and for restrained

eaters (classified by a restraint score >10 on the TFEQ) than for unrestrained eaters.[57] In contrast,

Epstein et al. discovered that only intensity was related to BMI for high-energy dense food items,

and this finding was robust in that the sample was very diverse, including participants of

different sex, age, BMI, and demand across different types of foods (low energy dense vs. high

energy dense).[25] In addition, amplitude (intensity) and persistence (elasticity, breakpoint, P_{max},

O_{max}) were reported to be strong predictors of habitual energy intake in subjects, measured by

repeated 24-hr recalls.[25]

Lumley et al. investigated how human consumption of a Western diet (high in added

sugars [AS] and saturated fat) related to DD for hypothetical monetary rewards and food

rewards, TFEQ, and other self-reported measures of impulsivity.[58] Participants who consumed

Western-style diet, indicated by the Dietary Fat and Sugar Scale (DFS), were more impulsive on

the hypothetical food DD task, choosing the smaller, immediate but less preferred food option

more often than a larger, more preferred option available after a delay, and this result was

independent of BMI status.[58] In addition, dietary restraint and disinhibition measured on the

TFEQ were significantly correlated with impulsivity measured on the monetary DD task.[58]

Lumley et al. also reported that high BMI correlated to higher self-reported impulsivity measured

on the Barratt Impulsivity Scale (BIS).[58] Since impulsivity has been reported to be more

common in overweight obese individuals, and a Westernized diet can contribute to weight gain

and obesity, it was hypothesized by Lumley et al. that impulsivity precedes weight gain instead

of resulting as a consequence of weight gain.[58]

Research investigating the relationship between physical activity and DD has just

recently started to populate. Tate et al. investigated how discounting rates differed between older

adults above the age of 60 years old in rural Arkansas between exercisers vs. non-exercisers.

Exercisers indicated a score of 20 on the vigorous activity index of the Yale Physical Activity

Screener, indicating they exercised at least 3-4 times per week, and that they were purposely

exercising for health benefits. The authors reported that exercisers had significantly lower DD

rates than non-exercisers, and inferred that exercisers viewed the long term healthy rewards of

exercise as more important than non-exercisers, who chose immediate rewards more

frequently.[59]

In contrast, Martin et al. discovered different results relating to DD and exercise,

although the DD task was slightly different.[60] In this study, endurance runners who ran >20 miles

per week and who have symptoms of exercise addiction indicated by the Exercise Addition

Inventory (EAI) reported greater addictive-like/impulsive behaviors measured by the DD task

and by activation of cognitive control regions in the brain indicated by magnetic imaging

resonance (MRI).[60] Results showed that when exercise was not allowed in the delay period of the

monetary DD task, greater preference for the smaller, immediate sum of money was preferred.[60]

Martin et al. explained that these results were comparable to other studies that investigated DD with populations who had drug addictions, in that discounting was steeper when choosing between a drug or a different delayed reward.[60] Although, greater discounting (more impulsive) was reported for runners when exercise was prohibited during the wait time for the delayed reward, limitations for this study include no control group, small sample size, possible confounding variables (such as BMI, socioeconomic status) were not included in the analysis, and the criteria for inclusion of endurance trained runners (at least 20 miles/week) does not necessarily exhibit highly endurance trained since the study did not assess past race competitiveness or an exercise test.

Overall, the above cross-sectional studies provide some supporting evidence that higher BMI, overweight/obesity, diet high in saturated fat and added sugars, women who are reinforced by high energy dense foods, dietary disinhibition, and high discounting rates are related. Cross-sectional studies investigating the influence of physical activity on DD are limited, conflicting, and are not generalizable. Additional research has been conducted using animal models to test the influences of a controlled diet and physical activity on DD measures using experimental and longitudinal designs, and two longitudinal studies investigated how an exercise intervention impacted DD rates in low-active people.

Steele et al. investigated the effects of a diet on DD in rats. The rats were fed either a high fat (HFD), high sugar (HSD), or a regular chow (Group C) for 8 weeks.[61] All rats were fed a diet composed on 101.75 kcals: Group C consumed 25 grams of standard rat chow (4.07 kcal/g), the HFD group consumed 15 grams of regular chow plus 4.38 grams of hydrogenated vegetable fat (9.3 kcal/g), which provided 40% more kcals from fat compared Group C, and the HSD group consumed 15 grams of regular chow plus 10.33 grams of sucrose (3.94 kcal/g) that was

mixed into unflavored gelatin.[61] Susceptibility to impulsive decisions was measured by a DD task, and was assessed when rats were fed the intervention diet (HFD, HSD, group C), and when they returned to a regular chow regular following the experimental diet.[61] When the HFD group began consumption of normal chow following the experimental phase, the rats preferred more longer, later (LL) rewards than more smaller, sooner (SS) rewards, in contrast to preferring more SS rewards when consuming the HFD.[61] In addition, HF and HS groups both made significantly more impulsive choices (chose more SS rewards) and less LL rewards when on the diet compared to group.[61] It is important to note that this diet-induced impulsivity was found in animal models and cannot directly be generalized to humans.

Strickland et al. investigated discounting in sedentary and endurance trained rats.[62] During the 11-week study, 16 female rats were allocated to an operant chamber that either contained a wheel for exercise or did not contain a wheel. At week 7 of the study, the DD task was assessed through food choice and forced trials, where two levers were placed in the cage to represent the immediate and delayed food option, and a white light was lit over the lever when food was available after a delay. Results revealed that the physically active rats chose delayed rewards more often and demonstrated a reduced sensitivity to the delayed reward compared to the sedentary rats.[62] Longitudinal studies in humans have also investigated how physical activity moderates discounting and have shown similar results.

Sofis et al. investigated the effects of an effort-paced physical activity (PA) intervention, using rate of perceived exertion (RPE) as a way to monitor effort, on reducing DD values, and if these reduced DD values were maintained one month post exercise intervention using two similar experiments.[63] Four (n=4) participants wore Fitbit physical activity trackers to record steps taken during the baseline and physical activity intervention period.[63] DD was measured

three times per week during the two-to-three week baseline period in which habitual steps were recorded, and was measured three times per week during the eight-week PA intervention. One month following the PA intervention, DD task was assessed again for the final time. Fitbit data was not analyzed during the 1-month post-experiment phase since they were rarely worn by participants. Results showed that the PA intervention increased mean number of steps per day and decreased DD rates for three out of the four participants, but was the results were not significant or conclusive since confounding variables, such as BMI and education status, were not assessed and may have played a role in the decreased DD values.[63]

In a second experiment by Sofis et al, 12 females participated in a similar effort-paced PA intervention.[63] During baseline, participants completed the DD task three times per week and the International Physical Activity Questionnaire (IPAQ) was completed one time per week.[63] The PA intervention was 7 weeks long and DD was assessed three times per week.[63] During the 1-month maintenance phase, the IPAQ and DD task were completed once a week for four weeks. Sofis et al. reported a significant reduction in DD throughout the experiment.[63] From baseline to treatment, DD values (measured by taking the ln of the k value) reduced by an average of 17.6% during treatment, and from baseline to maintenance, DD values reduced by an average of 19.9%.[63] Lastly, there was a significant correlation between the number of exercise sessions attended and the percent reduction in DD value.[63] From these two experimental studies, as well as the cross-sectional study by Tate et at., there is some evidence that increased physical activity is associated with decreased discounting, indicating that people who exercise more are less impulsive and place more value on larger, delayed rewards than less physically active people.

The research on how DD and exercise correlate is limited. The rat study by Strickland et al. and the PA intervention studies by Sofis et al. are the first to our knowledge to compare DD

and exercise in longitudinal, experimental models. To our knowledge, the proposed study will be among the first to investigate possible correlations between DD and PA in young males, investigate if DD and FPT measures change in response to an acute, high-fat diet (HFD), and determine if differences in response to diet manipulation exist depending on habitual physical activity level. In addition, it will be the first to investigate if there are differences in DD and cognitive restraint and disinhibition scores reported by the TFEQ in sedentary or endurance trained males response to a HFD.

Objectives

The purpose of this study is to investigate whether acute consumption (5 days) of a high-fat diet (HFD) changes a person's ability delay gratification and if there are differences in how rewards are valued between sedentary and endurance trained males. In detail, our objectives are:

1. To determine if DD, the food purchase task measures of demand elasticity and intensity, and the TFEQ measures of restraint, disinhibition, and hunger are different between sedentary and endurance trained men at baseline.

2. To determine if acute consumption of an isocaloric HFD alters DD, the food purchase task measures of demand elasticity and intensity, and/or TFEQ measures of restraint, disinhibition, and hunger.

3. To determine if there are differences in the response to acute consumption of an isocaloric HFD in DD, the food purchase task measures of demand elasticity and intensity, and TFEQ measures of restraint, hunger, and disinhibition in sedentary vs. endurance trained men.

4. To determine if associations exist between the constructs of the TFEQ, the food purchase task measures of demand elasticity and intensity, and DD.

It is hypothesized that discounting, demand elasticity, and demand intensity will be higher in the sedentary men compared to the endurance trained men. In addition, it is hypothesized that the high-fat diet intervention will increase discounting rates, regardless of exercise status. For TFEQ measures, it is hypothesized that sedentary individuals will have higher restraint scores at baseline and restraint scores will be negatively correlated with discounting rate; higher disinhibition scores will be positively correlated with higher discounting rates; and higher hunger scores will be positively correlated with demand intensity and elasticity.

Table 1. Literature Review Summary

Authors	Population	Study Design	Delayed Discounting	Additional Measures	Measurements	Results
Cross-Sectional Studies						
Appelhans et al. 2011	n=62 Females only, 18-45 Overweight and obese BMI 25-39.9 Did not screen for alcohol, drug, or cigarette use, but were instructed to refrain from caffeine and alcohol in the morning and not to smoke 1 hr before task	Consumed a preload of bland oatmeal until they reported being, "comfortably full," then completed self-report measures and DD tasks, took a 3-min break, then completed the laboratory taste test after 15-20 min of comfortable fullness	**Completed:** one time, when "comfortably full" Computerized choice task, hypothetical monetary reward at 7 different delays Delay amount: $100	-Power of Food Scale	-Ht, wt, BMI -Demographics and health history -k values and indifference points (DD) analyzed using AUC -Palatability – 0 (not at all) to 100 scale (extremely like) -Energy intake in taste test	Participants with high DD and increased sensitivity to food reward exhibited greater palatable food intake independent of homeostatic hunger
Appelhans, et al. 2012	n=78 Females only, 18-45 Overweight and obese (BMI 25-39) <u>Exclusion criteria:</u> any eating disorder problems Did not screen for alcohol, drug, or cigarette usage	Baseline screening of anthropometrics, DD task, instructions on diet recording, and received information on the DGA's. Then recorded diet for 7 days, and returned to lab to review completed dietary records	**Completed:** one time, not specified level of hunger or fullness, before 7 days of diet recording Computerized choice task for hypothetical monetary rewards Delay amount: $100 at 7 different delays (1 day to 5 years)	N/A	-Ht, wt, BMI -Demographics and health history -k values and indifference points (DD) – analyzed using AUC -Nutrient analysis of food records -Amount of home-prepared, ready-to-eat, and away-from-home foods were consumed	DD was unrelated to the frequency of consumption of home-prepared, ready-to-eat, and away-from-home foods, but greater DD values were associated with greater energy intake when subject's consumed ready-to-eat and away-from-home foods, but not home-prepared foods
Ely, et al. 2015	n=78 Females only Normal weight Did not screen for alcohol or drug abuse, or smoking	Measure of hunger and fullness using VAS, hedonic hunger on 1-5 scale using Power of Food Scale (PFS), then EI of oatmeal before DD task, repeat VAS hunger and fullness, and concluded with a sham taste test of palatable foods; 7-point Likert scale	**Completed:** one time, when full Computerized, choice task, hypothetical monetary discounting only Delay amount: $100, delay times not specified	-Power of Food Scale (PFS) - measures a person's appetitive drive to consume palatable foods in absence of homeostatic hunger -VAS subjective hunger and fullness -7-point Likert scale of study snack foods used in taste test	-Ht, wt, BMI -Demographics and health history -k values and indifference points (DD) – analyzed using AUC	DD and PFS did not significantly interact to predict highly palatable food intake Women with high PFS score and high DD consumed more total food than those with high PFS and low DD
Epstein et al. 2014	n=199 Females only All BMI ranges Did not screen for alcohol, drug, or cigarette usage	Same day recall and hunger scale were completed; subjects were given a preload of a Nature Valley granola bar (2 kcal/kg bw), and completed food reinforcement and DD tasks.	**Completed:** one time, subjects refrained from eating or drinking 2 hrs prior to each study session Hypothetical monetary rewards, completed using index cards Delay amount: $10 and $100 at 7 delays (1 day to 2 years)	-TFEQ -RRV of Food task: assessed the RRV of low energy dense (LED) and high energy dense (HED) foods using a computer program -VAS hunger and liking scale – before preload, and before and after RRV task	-Ht, wt, BMI -Demographics -Highest reinforcement schedule subject completed to gain access to preferred LED and HED food -k values and indifference points – analyzed using AUC	-High RRV and high DD interact to predict high BMI -Lowest BMI was found in women who found LED foods reinforcing and have low DD

Epstein et al. 2018	n=297 Males and females All BMI ranges Did not screen for alcohol, drug, or cigarette usage	Participants from two separate studies were assessed: Grocery store study and Multisite Intervention Neuroimaging Delay Discounting (MINDD). Grocery store participants completed food purchase task for low and high energy dense foods that they could consume over a 1-day period, and MINDD study participants completed purchase task based on their "favorite" snack food that they could consume in one 30-min. sitting	N/A	N/A	-Ht, wt, BMI -Demographics -Food purchase task variables: amplitude (demand intensity) and persistence (elasticity, P_{max}, O_{max}, and breakpoint)	-More elastic for high energy dense foods than low energy dense foods for all participants -Amplitude and persistence accounted for >90% of total variance in food reinforcement -Intensity was related to increased BMI
Jarmolowicz et al. 2014	n=100, 18-55 yo Males and females All BMI levels <u>Exclusion criteria:</u> any current or past abuse of illicit substances, use of psychotropic medicine, or diagnosis of sever neurological or psychiatric illness Gambling and cigarette usage was not screened for	Participants entered the lab once, anthropometrics and demographics were measured. Participants completed the temporal discounting rate questionnaire, and two other questionnaires assessing depression and behavioral inhibition and approach	**Completed:** one time, degree of hunger/fullness or fasted/non-fasted was not reported MCQ, 27 choice trials between hypothetical, smaller immediate rewards vs. larger, delayed reward Calculated 4 temporal discounting rates: one for each small, medium, and large reward sizes, and one across all reward sizes	-Beck Depression Inventory-II (BDI-II) – higher scores indicated more depressive symptoms -Behavioral Inhibition Scale/Behavioral Approach Scale (BIS/BAS) – assessment to assess tendency to avoid unpleasant stimuli and seek pleasant stimuli	-Ht, wt, BMI -Demographics: education level and income - *k* values and indifference points (DD) -Depression level -Behavioral inhibition level, and subscales of the BIS/BAS: drive, fun-seeking, and reward responsiveness	DD rate is strongly correlated with BMI, even when covariates of age, sex, education level, annual income were included in the analysis Overweight/obese adults were more likely to choose the smaller, immediate monetary reward More depressive symptoms and higher fun-seeking behaviors (reported on BIS/BAS) were associated with greater DD
Lumley et al. 2016	n=56 Males and females Normal BMI <u>Inclusion criteria:</u> scored in the upper or lower quartile of the DFS (i.e. extremely high or low consumption of sat. fat or AS <u>Exclusion criteria:</u> no chronic medical/psychiatric condition, eating related disorders Did not screen for alcohol, drug or cigarette usage, or gambling problems	Two studies were done simultaneously 1) Subjects completed a FFQ, demographics, BIS, and dietary fat and sugar scale (DFS) 2) Subjects who scored in the higher and lower quantiles of the DFS were included, and completed questionnaires: demographics, TFEQ, UPPS, monetary DD task, MFFT. Then participants filled out the Food Preference test, completed the DFS for a second time, and completed the food DD task	**Completed:** 1 time, did not eat or drink for 2 hrs prior to the tasks **-Hypothetical monetary rewards** – addressed using a questionnaire, delay amount not specified. 21 trials addressed in a fixed, random order for each participant **-Hypothetical food rewards -** choose between a small portion of a less preferred food now vs. a small portion of a preferred food after a delay (6 delay periods ranging from 0-120 minutes). Participants indicated less, moderate, and highly preferred foods from a list of 34 palatable snack items	-Dietary Fat and Sugar Scale (DFS) – assess intake of foods rich in sat. fat and AS, higher scores indicating for frequent consumption of sat. fat and AS (26-130) -Barratt Impulsivity Scale (BIS) (refer to Weller et al.) -TFEQ -Physical Activity Level -Urgency, Premeditation, Perseverance and Sensation Seeking (UPPS) – assess 4 facets of impulsivity -Matching Familiar Figures Task (MFFT)	-BMI -Demographics -Physical Activity Level -Hierarchical regression analyses were conducted for scoring the questionnaires (UPPS, MFFT, etc.) -DD monetary task: calculated the mean number of immediate monetary choices, compared to TFEQ scores -DD food task: fit line to each participant's data: number of immediate choices at each delay	Western-style diet (high in sat. fat and AS) indicated by high score on the DFS was associated with greater trait Urgency and higher DD on DD food task Subjects with higher DFS scores (consumption of a highly Western diet) chose more immediate, available, less preferred food rewards over a more preferred food as the delay to receive the more preferred food increased Restraint and disinhibition (from TFEQ) were associated with high impulsivity measured on the monetary DD task

Martin et al. 2017	n=17, 20-60 yo Males and females BMI was not specified Runners had to run at least 20 miles/wk Exclusion criteria: diagnosis of major illness, pregnancy, diagnosis of neurological or psychiatric disorder (including eating disorders), currently taking psychotropic meds.	First visit: baseline screening, completed measures of exercise addition and heart rate variability; second visit: DD task and MRI session	**Completed:** 1 time, did not specify level of hunger or fullness Hypothetical monetary choice task; on half of the trials participants were instructed that they were not allowed to exercise during the delay	-Exercise Addition Inventory (EAI)	-*k* values and indifference points (DD); analyzed using AUC	Endurance runners had a decreased ability to wait for the delayed reward on the DD task
Nederkoorn et al. 2006	n=56, <50 yo Females only Normal weight and obese Did not screen for alcohol, drug, or cigarette usage	Normal weight and obese women completed four measures to test their susceptibility to impulsivity	**Completed:** one time, degree of hunger/fullness or fasted/non-fasted was not reported Hypothetical monetary choice task, using index cards, Delay amount $1000 following 7 delays (7 days to 25 years)	-Stop Signal Task – measures inhibition -Eysenck Personality Profiler – measures impulsiveness as a personality trait -The Dutch Sensation Seeking Scale – measures a person's drive to take risks and engage in intense experiences	Ht, wt, BMI -Indifference points and *k* values (DD task) were analyzed using the hyperbolic discounting equation to calculate discounting value and by measuring AUC	No significant differences between obese and normal weight women on the DD task were found
Rasmussen et al. 2010	n=60 Male and female undergraduate students (n=43 females) Participants were screened for cigarette, drug, and alcohol usage, and current dieting practices	Participants entered lab, measured ht, wt, BMI, and PBF; completed self-report measures, DD and PD	**Completed:** one time, participants were not asked to refrain from eating or drinking prior to the task Computerized choice task, hypothetical monetary and food rewards Delay amount ($) DD: $10 after 5 delays (1 to 365 days), PD: $10 after varying probabilities of receiving the reward Delay amount (food): DD: 10 bites of favorite food after 5 delays (1 to 365 days) PD: 10 bites of food varying probabilities of receiving the reward	-Alcohol Use Disorders Identification Test	-Ht, wt, PBF (using Tanita 2204 Body Fat Scale) -Indifference points (DD) – analyzed using the hyperbolic discounting function and AUC -Self-reported subjective hunger level prior to DD -Reported hrs since last meal prior to DD	PBF was a significant predictor of discounting patterns for food DD and PD only, not significant for monetary discounting Found no relationship between subjective hunger, hrs since last meal or snack, and rates of DD for food or money Analysis found that women had steeper discounting on DD and PD food tasks than men, suggesting women make more impulsive decisions towards food

Reslan et al. 2012	n=21 Females only Normal weight, overweight, and obese (BMI) Non-smokers or nicotine users Did not screen for alcohol or drug use	Participants completed a food reinforcement task: 11 concurrent choices between a high-fat/high-sugar food and a high-fat/low sugar food where they could work for foods by clicking the mouse to assess food demand. Number of responses needed to receive food increased exponentially for subsequent trials	**Completed:** one time, degree of hunger/fullness or fasted/non-fasted was not reported Computerized choice tasks between a small immediate amount of Hershey's chocolate kisses vs. a larger amount of chocolate kisses over 5-180 minute delays.	-TFEQ	-Ht, wt, BMI -Demographics -DD: k values analyzed using the hyperbolic discounting function	-High-sugar/high-fat food was more inelastic for overweight vs. non-overweight subjects, and for restrained eaters vs. non-restraint eaters -Participants who were more impulsive (high k values) exhibited more elastic demand curves, i.e. more price-sensitive
Rollins, et al. 2010	n=28 Females only Non-obese (BMI <30) Excluded individuals who were current or past smokers, had substance abuse problems, gambling problems, or eating disorders	Participants did not eat/drink for 3 hrs prior to each of the 3 sessions. Completed each of the following tasks on different days, 3 sessions total: **1.** Ad libitum eating task – participants were instructed to consume as much of the presented foods as wanted, stayed in study room for 20 min **2.** RRV task – work at a computer to obtain portions of preferred food, latter computer with an alternative to food was provided, and **3.** DD task	**Completed:** one time, participants did not eat or drink 3 hrs prior to the test DD was not computerized. Done using index cards, hypothetical delay amount of $10 was titrated at 10 different time delays (1 day to 2 years)	-TFEQ -The Binge Eating Scale -Questionnaire of Eating and Weight Patterns -24-hr recall (to ensure compliance to study foods) -Hunger and liking Likert scales before and after each of the three tasks	-Ht, wt, BMI -Demographics and heath hx -DD: Indifference points and k values– analyzed using the hyperbolic discounting function and AUC -Hunger and liking – Likert scale -Nutrient analysis of 24-hr recall	Women who exhibited higher RRV of food consumed significantly more energy during the ad libitum eating task only when k values were high (indicating high DD) High RRV of food was a marginally significant predictor for energy intake for women who had low k values
Tate et al.	n=137 Both genders >60 yrs old Inclusion criteria: sedentary or score of 20 on vigorous activity index (VAI) of Yale Physical Activity Survey – exercise of at least 50 min. or more Exclusion criteria: cognitive impairment and inability to exercise because of physical impairment	Participants filled out the vigorous activity index (VAI) on the Yale Physical Activity Survey (YPAS) to determine exercise level, then completed the DD task	**Completed:** 1-time, degree of hunger/fullness or fasted/non-fasted was not reported MCQ, 27 choice trials between hypothetical, smaller immediate rewards vs. larger, delayed reward	-VAI of YPAS -Behavioral Risk Surveillance System (BRFSS) demographic information	-Demographics -DD task – k values were used to calculate the discounting rate	Exercising older adults had lower discounting values than non-exercising

Weller et al. 2008	n=55 Male and female Obese participants (BMI) and normal weight (BMI 18.5-24.9) Both genders, college aged students (18-23) <u>Exclusion criteria:</u> current or past smoker, current or prior substance abuse problems, gambling problems, or eating disorder	Anthropometrics and questionnaires were measured and administered in a laboratory setting. Participants then completed both versions of the DD task, in which the delay option was either $50,000 or $1000	**Completed:** one time, hunger level was not specified Computerized choice task, 12 practice trials followed by the experimental trials Two versions of the task at 7 different delays: Version 1 had a delay reward of $50,000 and Version 2 had a delay reward of $1000	-Shipley Institute of Living Scale (estimated IQ) -Average gross income of household in which the participant was raised -Barratt Impulsiveness Scale (BIS) – addresses 3 facts of impulsivity: motor, inattention, and non-planning	-Ht, wt, BMI -Matched participants by gender and age -DD: Indifference points – analyzed using AUC	Obese women showed significantly higher DD rates than normal weight women, results were not significant for normal and obese men DD differences in control and obese women were not related to age, income, or IQ
Yeomans et al. 2008	n=147 Females only All BMI levels, (28 overweight, 3 obese) Did not screen for alcohol, drug, or cigarette usage	Participants filled out the TFEQ and were categorized as high or low on both the restraint and disinhibition scales, then came into the lab to complete the DD task and two other impulsivity questionnaires	**Completed:** one time, degree of hunger/fullness or fasted/non-fasted was not reported Computerized hypothetical monetary rewards Delay amount: $10 at 6 different delays (0 to 365 days)	-TFEQ -Barratt Impulsiveness Scale – measures thoughts and behaviors on a 4-point Likert scale -Dickman Impulsivity Inventory – measures functional and dysfunctional impulsivity	-Ht, wt, BMI -Demographics -Indifference points (DD) and k values– analyzed using the hyperbolic decay function -Level of impulsivity reported on questionnaires -High or low restraint -High or low disinhibition	Women who scored higher on the TFEQ-D also had higher DD scores; i.e. more impulsive Found that scores on the TFEQ-D are correlated with impulsivity, but not TFEQ-R Found no relationship between DD and BMI
Experimental/longitudinal studies						
Sofis et al. 2017 (study 1)	n=4 Male and female	Participants met with a researcher to assess goals and fitness level. Baseline phase lasted 2-3 wks and subjects wore a Fitbit to track steps and completed DD task 3x per week. Participants a began time and effort-paced PA intervention which were coach led 3 times/week for 45 min for 8 weeks. Subjects returned after 1 month to assess DD and return Fitbits	**Completed:** 3x/week for: 1-3 weeks during baseline (depended on participant), 8 weeks during PA intervention, then once post PA intervention Hypothetical MCQ, 27 trials completed via Qualtrics	Mental health assessment PA measurement: Fitbit Charge HR Rate of Perceived Exertion (RPE)	-Demographics -Steps per day -Rate of discounting (k) and indifference points	Results partially showed that the PA intervention resulted in decreased discounting, but results were inconclusive
Sofis et al. 2017 (study 2)	n=12 Females only Did not screen for alcohol, drug or cigarette usage, or gambling problems	During baseline: DD task was completed 3x/week and the International Physical Activity Questionnaire (IPAQ) was completed 1x/week. Then, participants engaged in a 7-week long, distance and effort based, PA treatment and DD was assessed 3x/week. During the 4-week maintenance phase, the IPAQ and DD task were completed once a week	**Completed:** 3x/week for: 1-2 weeks during baseline, 8 weeks during PA intervention, then once post PA intervention Hypothetical MCQ, 27 trials completed via Qualtrics	IPAQ – 1x/week Rate of Perceived Exertion (RPE)	-BMI -Demographics - highest education level	Discounting was reduced by an average of 17.6% from baseline to during treatment Significant correlation between higher number of exercise sessions attended and reduced DD rates

Steele et al. 2017	n=28 rats Males only All BMI levels	Fed a normal, consistent diet of chow before diet intervention. Rats were fed a high fat (HF), high sugar (HS), or normal chow diet (Group C) for 8 weeks. Following 8 weeks, rats completed pre-training prior to impulsive choice (IC) task. Then, continuing on the diet, they performed the IC task for 100 days (14 weeks). Then, rats stopped the diet they were on, and consumed regular chow and performed the IC task.	**Completed:** when not yet fed DD trials: mix of free and forced trials	N/A	-Body weight (5 times per week) -Grams and kcals of food eaten by rats after administration of HF, HS, or regular chow -Impulsive choice measured by the DD task	Groups HS and HF had higher DD rates than Group C HS and HF continued to show more impulsive choice (less LL rewards chosen) following the HS or HF diet compared to Group C, but all groups showed lower DD rates during the off-diet phase
Strickland et al. 2017	n=16 rats Females only BMI not specified	11-week study where rats were randomly assigned to a sedentary or physical activity (PA) group – PA rats were given free access to a wheel in their cage. After 6-weeks, rats were restricted food to no less than 85% of and trained to press a lever used in the DD task	**Completed:** when not yet fed DD trials: 40 total, 10 forced trails and 30 free trials	N/A	-Impulsive choice measured by the DD task -Wheel revolutions/day for PA rats -Sensitivity to reinforcement the amount offered	DD was significantly lower in the PA rats compared to the sedentary rats PA decreased rat's sensitivity to delay and sensitivity to amount, meaning that PA rats chose greater delayed rewards more often but were not as sensitive to the amount of the reward (i.e. # of pellets)

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CHAPTER 2: Influence of a High-Fat Diet on Delay Discounting, Food Reinforcement, and Eating Behaviors in Sedentary and Endurance Trained Men

ABSTRACT

Delayed discounting (DD) and the food purchase task (FPT) are used to quantify how people make decisions depending on time to receive and amount of the reward, and to determine how reinforcing a food item is as the price increases. To our knowledge, how exercise status (sedentary vs. endurance trained) and a high-fat diet interact with discounting rates and the relative reinforcing value of a snack food has not been previously investigated. This study aimed to determine differences in discounting rates, demand elasticity and intensity, and eating behaviors between sedentary and endurance trained males, and how these measures may change in response to a high-fat diet. Using a controlled feeding study design, 10 males (n=7 sedentary, n=10 endurance trained) consumed an iso-caloric, standard diet (55% carbohydrate, 30% fat, and 15% protein) for 10 days, followed by a high-fat diet (55% fat, 30% carbohydrate, 15% protein) for 5 days. DD, FPT, and Three Factor Eating Questionnaire (TFEQ) were assessed at three time points: baseline, after the standard diet/before high-fat diet, and after the high-fat diet. Discounting rates were significantly different at baseline between sedentary and endurance trained males, with the sedentary males having higher discounting rates (mean difference 1.43, $p=.037$). Discounting rates for the whole sample significantly decreased between baseline (time 1) and post-STD diet/before HFD (time 2), between time 2 and after the HFD (time 3), and between time 1 and time 3 (all indicated by $p<0.05$). No group differences were noted over time for demand elasticity, intensity, or TFEQ measures (all indicated by $p<0.05$). These findings indicate that exercise and dietary changes may play a role moderating impulsive choice.

Keywords: delay discounting, impulsivity, food reinforcement, rewards, demand elasticity, behavioral economics, exercise, eating behaviors

INTRODUCTION

More than two-thirds of the population in the United States are overweight, and one in five adults do not meet the national physical activity guidelines.[1-3] A sedentary lifestyle is a risk factor for obesity[4], along with the current environment in Westernized societies. The environment is often described as "obesogenic," and is defined by Martin and Davidson as, "low cost, energy dense, highly palatable foods and beverages, and an abundance of external cues that keep thoughts of these foods and beverages almost constantly in mind." This type of environment is thought to disrupt a person's ability regulate energy intake by influencing intrinsic physiological controls, often leading to poor decisions and weight gain.[5]

Behavioral economics is used to study how individuals make decisions in the context of alternatives, and depending on their resources (i.e., time, money), in an environment where variable constraints, (e.g. effort required, cost of product, etc.) exist and are highly influencing.[6,7] Delayed discounting (DD), also termed present consumption bias and temporal discounting, is used as a theoretical approach to assess impulsivity and quantifies how a reward loses value as time to receive the reward increases.[8,9] High discounting indicate that a person more steeply discounts the value of the delayed reward, is reinforced by the immediate gratification of the small reward, and is ultimately more impulsive.[6,10]

Another use of behavioral economics is to assess the relative reinforcing value (RRV) of food, which is defined as the motivation to allocate food or the amount of work a person will give to obtain a food item, and can be assessed the food purchase task (FPT).[6,11] The FPT quantifies how much of a snack food a person would buy across a range of prices, and provides an index of demand elasticity and intensity.[11] Demand elasticity measures the change in the

amount of the commodity that is purchased as price increases, and intensity measures how much a person would consume if the commodity was free.[11]

Another factor that influences how people make food related decisions are their attitudes towards food. The Three-Factor Eating Questionnaire (TFEQ) is used quantify three constructs of eating behavior: cognitive restraint, disinhibition, and hunger.[12] Cognitive restraint is defined as a person consciously controlling food intake in order to prevent or promote weight loss; disinhibition measures the susceptibility to eat in response to stimuli, such as eating in an emotional state or response to stress, or inability to cease dietary intake when presented with large portions or many tasty options; and hunger is eating in response to physiological symptoms.[12,13]

Discounting may be higher in women,[14] and in overweight/obese individuals,[14,15] (although, conflicting, see Rasmussen et al[16] and Nederkoorn et al[17]), and in people with substance abuse problems.[18] In addition, discounting rates have been reported to remain relatively stable over time without intervention.[19,20] It has also been reported that discounting rates generally decrease with age,[21] but Kirby et al. reported a moderate increase in discounting rates over time in college students and suggested that college years may be an exception.[19] Higher discounting scores have been positively correlated with disinhibition scores,[22] and higher RRV of food in women.[23] In addition, higher discounting was associated with higher demand elasticity scores (indicating higher sensitivity to changes in price), but it was also reported that demand for high-fat/high-sugar foods was more inelastic for overweight participants and among those with had higher cognitive restraint score (>10 on TFEQ).[24] Consumption of a Westernized diet (high fat/high sugar), higher cognitive restraint and disinhibition were associated with higher discounting rates.[25]

Related to physical activity and exercise, an observational study reported that older adults (>60 years old) who exercised for health benefits (minimum of 50 minutes per week), had lower discounting rates than those who did not exercise.[26] In contrast, a study of endurance runners who had symptoms of exercise addiction reported higher discounting rates.[27] Although, in this study, participants were instructed that they were not allowed to exercise during the wait time for the delayed reward.[27] In addition, discounting rates decreased by 19.9% from baseline to maintenance following a 7-week effort paced physical activity intervention in a study of 12 females (n=12).[28] Similar findings were reported in a non-human study, where physically active rats demonstrated lower discounting rates than sedentary rats.[29]

One study conducted in rats evaluated changes in discounting rates following an 8-week high-fat diet (HFD) intervention, which consisted of 40% more calories from fat compared to the regular rat chow, discovered that rats began preferring sooner rewards (higher discounting) during the HFD vs. preferring more larger, later rewards when they resumed consumption of regular chow diet.[30] To our knowledge, no human studies to date have evaluated changes over time in discounting rates, demand elasticity and intensity, or measures of cognitive restraint, disinhibition, or hunger in response to a HFD in humans.

Our objectives were to determine (1) differences in discounting rates, FPT measures of demand elasticity and intensity, and eating behavior at baseline between sedentary and endurance trained males, (2) determine if acute consumption of a HFD using a controlled feeding study design alters discounting, demand elasticity and intensity, or eating behavior, and (3) if response to the HFD is different between sedentary vs. endurance trained adult males, and (4) explore associations between discounting, demand elasticity and intensity, and eating behaviors.

MATERIALS AND METHODS

Study sample and design

The Virginia Tech Institutional Review Board approved all study procedures before the onset of study recruitment. Maled ages 18-40, with a body mass index (BMI) <25 kg/m^2 were recruited from a local campus community in Southwest Virginia via flyers and word of mouth for participation. Individuals were included if they were either endurance trained ($\geq$5h/week of running or cycling and participation in $\geq$2 races of $\geq$10 kilometers within the last year) or sedentary to recreationally active ($\leq$2h/week of physical activity and no planned, intentional exercise), weight stable for the previous 6 months ($\pm$2.5 kg), and if habitual dietary fat consumption was <35% of kcals from fat as evidenced by a 4-day food intake record (FIR) and a brief dietary fat screener[31], provided informed consent, and agreed to comply with all study procedures. Exclusion criteria included dietary restrictions (vegetarian, vegan, does not eat red meat or food allergies), presence of a chronic or major disease, or risk for factors for disease (e.g. hypertension, hypercholesterolemia, prediabetes, etc.).

Procedures

The study protocol is depicted in Figure 1. Online screening included brief health history information and the brief dietary fat screener.[31] Baseline screening day 1/time point 1 (TP1) was assessed following a 12-hour overnight fast. Measurements obtained included demographics and health history assessed via a questionnaire; height and weight measured via a wall-mounted stadiometer (model 216; Seca and digital scale, Scale-Tronix 5002); blood pressure via an automated sphygmomanometer (Colin Press-Mate 8800); fasting plasma glucose (FPG), complete blood count (CBC), and lipid panel via a fasting blood draw; and physical activity level assessed using the Godin Leisure Physical Activity Questionnaire.[32] Baseline delayed

discounting (DD) task, food purchase task (FPT), and Three Factor Eating Questionnaire were administered. At the end of the session, participants were provided with instructions for completing a 4-day food intake record (FIR) to be completed on one weekend day and three weekdays to measure habitual dietary intake.

On baseline screening day 2, a cardiorespiratory fitness assessment (maximal oxygen consumption; VO2 max) was performed as a descriptive measure of aerobic fitness level, and was assessed according to usual laboratory procedures.[33] Briefly, participants ran at a comfortable speed (~6 mph) on a treadmill that increased in grade every two minutes until complete exhaustion, lasting ~10 minutes.[33] Open-circuit spirometry was used to measure gas exchange while exercising.[33] Dual-energy x-ray absorptiometry (DEXA) was used to assess body composition (percent fat mass and fat free mass). The 4-day FIR was returned by the participant and reviewed with a researcher to ensure accuracy and completeness, and dietary composition was analyzed utilizing Nutrition Data Systems for Research (NDS-R) version 2014. Participants were given a schedule on the next 16 study visits to ensure clarity and compliance with study measures (controlled feeding periods 1 and 2; time point 3).

The controlled feeding portions of the study began within one week of completion of baseline screening visit 2. Controlled feeding period 1 consisted of 10 days of an isocaloric, standard, lead-in diet (STD) that consisted of 55% carbohydrates, 30% fat (<10% saturated fat), and 15% protein and served to standardize baseline dietary consumption of participants. Following the STD, participants consumed an isocaloric high-fat diet (HFD) for 5 days that consisted of 30% carbohydrate, 55% fat (<25% saturated fat), and 15% protein. DD, FPT, TFEQ and body composition (DEXA) were reassessed at the end of each controlled diet period while fasted.

Controlled feeding

Both the STD and HFD were created by a research dietitian to match micronutrient composition using Nutrition Data System for Research (NDS-R [Version 2014; Minneapolis MN]. Energy needs per participant were estimated using the Mifflin-St Jeor equation and habitual dietary intake indicated by the 4-day FIR.[34] Participants were assigned a calorie level that was within 500 kcal of estimated needs, (i.e., 2000, 2500, etc.). Weight was measured each morning during the controlled feeding periods in the metabolic kitchen to ensure diets were iso-caloric, as evidenced by weight stability. Two optional snack modules (250 kcals each) were offered daily to promote weight stability and matched the macronutrient composition of each diet period. Calorie amounts were adjusted for participants if their weight fluctuated above or below their weight stability range for three consecutive days, which was indicated by ±1.0 lbs from first weigh-in of the controlled feeding period.

All food was prepared in a metabolic kitchen using a digital benchtop scale (Practum 5101-1S, Sartorius; Goettingen, Germany) and weighed out to +0.9 grams of menu amounts. Breakfast was consumed in the metabolic kitchen daily and supervised by research staff. All other meals, snacks, and beverages were provided in a cooler for participants to take for the day. Participants were instructed to consume all provided food and drink with the option to consume two snack modules, and as much water (without additives) as they preferred. Microwave instructions were provided for heating refrigerated or frozen meals items. Participants returned food and beverage containers unwashed and the research staff weighed each container to report actual consumption. Participants were also asked to report any uneaten foods or beverages.

Adjusting Amount Delayed Discounting Task

The adjusting amount discounting task was assessed via a laptop computer at three time points (Figure 1). In this series of questions, the immediate and delayed reward are both monetary rewards. The task uses an adjusting algorithm to determine the amount of money that is equivalent to $1000 now at seven different delay periods of 1 day, 1 week, 1 month, 3 months, 1 year, 5 years, and 25 years.[35] At each delay, the immediate and delayed rewards are randomly positioned on opposite sides of the screen. Depending on the option that the participant chooses, the reward titrates up (delayed reward chosen) or down (immediate option chosen) by $250, and a new choice is presented on the screen. The trial continues to titrate until the participant switches from choosing the delayed reward to choosing the immediate reward (or vice versa), known as the indifference point, or amount at which the immediate and delayed rewards are valued equally for a specific delay period.[35] For each delay period, there are five difference choice trials, and the immediate amount is adjusted by half of the amount of the previous adjustment. This generates 32 different indifference points.

Discounting rates are then determined by Mazur's (1987) hyperbolic free parameter k, which is calculate by the function $V=A/1+kD$, where V represents the subjective value of the delayed reward (indifference point), A is the amount of the delayed reward, D is the delay, and k is the parameter that captures how steeply the reward decreases in value as the delay period increases.[36]

Food Purchase Task

The Food and Activity questionnaire was given to determine a participant's "favorite" snack food from a variety of high energy dense foods, including Cheetos®, Cheez-Its®, Chips Ahoy!® cookies, nacho cheese Doritos®, Fritos®, M&M's®, Oreos, Lay's® potato chips, Reese's

® peanut butter cups, or Swedish fish candy.[11] This task assesses how many standardized, 20-gram servings of a subject's favorite snack food he/she would purchase across a range of prices, including $0.01, $0.05, $0.10, $0.25, $0.50, $1, $2, $5, $10, $20, $40, $80.[11] Hypothetical purchases were used to determine demand elasticity and demand intensity, calculated from the following equation: $Q = Q_0 * k(e^{-\alpha Q_0 C} - 1)$, where C is the amount of consumption of the snack food; Q_0 is demand intensity; i.e. how much a participant would consume if the commodity was free; α is demand elasticity, which measures the change in the amount of the commodity that is purchased as the price of that commodity increases and is the slope of the equation; and *k* is the span of the function is $\log_{10}$ units and is consistent when analyzing all participant data. In this equation, α and Q_0 are free to vary.[37] Demand elasticity and intensity are used to determine the reinforcing value of a participant's favorite snack food.[37]

Three Factor Eating Questionnaire (TFEQ).

The TFEQ is a 51-item self-report questionnaire to assess three constructs of eating behavior: restraint, disinhibition, and hunger.[12] The questionnaire contains 21 questions to assess restraint, 16 questions to assess disinhibition, and 14 questions to assess perceived hunger. Higher scores represent higher levels of dietary restraint, disinhibited eating, and perceived hunger.

Statistical Analysis

Data was analyzed using statistical analysis software (IBM SPSS Statistics Version 24 Armonk, NY). All statistical tests were set with an a priori significance of α=0.05. Descriptive statistics were used to characterize participant demographics, BMI, baseline weight, percent body fat, fat screener score, VO_2max, and self-reported habitual dietary intake for baseline participants only and completed participants. Independent samples t-tests were used to compare baseline measures between sedentary and endurance trained groups. Pearson's correlations were used to determine

associations baseline discounting rates, demand elasticity, demand intensity, or measures of the

TFEQ and other baseline measures. Weight stability was analyzed using paired t-tests to

compare weight between the first day of the STD diet, day 1 of the HFD, and day 5 of the HFD.

Dietary compliance was assessed from metabolic kitchen records. One-way mixed repeated

measures analysis of variance (ANOVA) were used to determine if discounting rates, demand

elasticity, demand intensity, cognitive restraint, disinhibition, or hunger changed from time

points (within-groups factor), and if there were differences between sedentary and endurance

trained groups (between-groups factor). If there was a significant interaction by time, post-hoc

paired t-tests were used to determine where the differences existed. Discounting rate k, demand

elasticity α, and demand intensity Q_0 were all log transformed to ensure normality. Two

participant's FPT was recoded due to requesting the same amount of servings at every price.[38]

One participant did not complete DD task, FPT, or TFEQ at any time point, therefore was

excluded from all analyses. Another participant did not complete the full TFEQ at the final time

point, therefore was excluded from the repeated measures ANOVA for cognitive restraint,

disinhibition, and hunger. One endurance trained participant dropped out following the second

time point, therefore was excluded from all repeated measures analyses. Prior to running

analyses, outliers were determined by the inspection of boxplots greater than 1.5 lengths from the

edge of the box. For the measure of demand elasticity, there was one outlier in the endurance

trained group at time point 2. For the measure demand intensity, there was one outlier in the

endurance trained group at time point 1 and 2 outliers in the endurance trained group at the final

time point; for the measure of restraint, there was one outlier in the endurance trained group at

the second and third time point; and for the measure hunger, there was one outlier in the

endurance trained group at time point 1. Repeated measures ANOVA were performed with and

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without outliers for demand elasticity, demand intensity, restraint, and hunger, and results of the repeated measures ANOVAs did not change with or without outliers. Therefore, these data points were included in the following analyses. Pearson's correlations were used to assess correlations between variables.

RESULTS

Participant flow is presented in Figure 2. Of the 29 participants enrolled, 18 completed baseline testing and 10 completed both controlled diet phases. Participant demographic characteristics, VO_2max, and self-reported habitual dietary intake data are provided in Table 1 for baseline participants only (n=17 total; n=5 sedentary, n=12 endurance trained) and for completed participants (n=10 total; n=3 sedentary, n=7 endurance trained). To note, one baseline participant did not complete baseline screening visit 2, therefore is not included in the mean VO_2max or mean habitual dietary intake (n=16 total; n=5 sedentary, n=11 endurance trained). Participants were male adults ages 18-35, and predominately white. For the baseline sample, VO_2max were significantly lower for the sedentary group compared to the endurance trained group. Percent body fat (%BF) was also significantly different between groups, with lower percent body fat in the endurance trained group. Statistically significant differences remained for just those who completed the study for VO_2max and body composition. Fat screener scores were significantly different between activity groups for completed participants only, with a mean difference of 11.8 (95% CI 1.504 to 22.16, t(8)=2.643, *p=*.03).

For baseline habitual dietary intake, there was only a significant group difference for percent energy intake from saturated fat. Among completers, there was no significant group differences for any habitual dietary intake variables.

Controlled Feeding Diet Compliance

Dietary compliance was assessed in two ways: using daily menu records of food given and returned and by weight stability. Actual mean percent consumption/day of macronutrients of the diets consumed were compared to the target macronutrient percentages of each diet provided. For the STD, mean consumption per day of percent energy from carbohydrates, fat, and protein were 54.5%, 30.3%, and 15.2% respectively, consistent with the targeted STD composition of 55% carbohydrate, 30% fat, and 15% protein. For the HFD, mean consumption per day of percent energy from carbohydrates, fat, and protein, were 31.3%, 53.7%, and 15.1% respectively, consistent with the targeted HFD composition of 30% carbohydrate, 55% fat, and 15% protein. Participants body weight was stable during the controlled feeding periods (Table 2), with no significant changes over the controlled feeding periods.

Baseline (TP1) Between Group Differences in Main Outcomes

There was a significant difference in discounting rates at baseline between groups ($p=.037$), with sedentary men demonstrating higher discounting rates (-1.95±1.42) than endurance trained males (-3.37±1.02) (see Figure 5b). Restraint, disinhibition, hunger, demand elasticity (α), and demand intensity (log Q_0) were not statistically difference between groups at baseline (all p-values >0.05).

Baseline (TP1) Correlations

For TFEQ measures, there was a significant moderate positive correlation between the following measures: disinhibition and hunger scores ($r=0.6$, $p=0.008$); demand elasticity and restraint scores ($r=0.5$, $p=0.045$) (Figure 3); and between demand intensity and hunger ($r=0.6$, $p=0.018$) (Figure 4). There were no other significant baseline associations between variables (all p-values >0.05).

Differences Over Time and Between Groups

Delayed Discounting Rates

There were no group differences in DD over time. Of importance, mean discounting rates were significantly different over the three time points (F(1.121, 7.844)=7.86, *p*=.022) in the full sample. There was a significant mean decrease from between TP1 and TP2 of 0.609 (*p*=0.043); between TP2 and TP3 of 0.218 (*p*=.045); and between TP1 and TP3 of 0.822 (*p*=0.034). See Figures 5a and b.

Demand Elasticity

There was no statistically significant interaction between activity groups and time on demand elasticity, (F(2,14)=.344, p=.715). Also, demand elasticity was not statistically significant between time points (independent of activity group) (F(2,14)=.982, *p*=.399) See Figures 6a and b. When excluding one outlier participant (as mentioned in statistical analysis), there was a statistically significant difference between TP1 and TP2, with a mean decrease of -.131 (95% CI of -.2290 to -.0325, t(7)=-3.148, *p*=.016).

Demand Intensity

There was no statistically significant interaction between exercise groups over time on demand intensity (F(2,14)=2.281, p=.139). In addition, there were no significant differences over time for demand intensity in the full sample. See Figures 7a and b.

Cognitive Restraint, Disinhibition, and Hunger

There was no significant difference by group or over time in cognitive restraint, disinhibition, or hunger (Table 3).

Correlations Between Differences in Outcomes Over Time

There was a strong negative correlation between change in restraint scores and change in disinhibition scores from over the HFD phase (*r*=-.689, *p*=.04) in the full sample. There were no

significant correlations between: change in discounting rates, demand elasticity, demand intensity, restraint, or disinhibition between over the STD or HFD phases.

DISCUSSION

This is the first investigation to evaluate differences in discounting rates, demand elasticity, and demand intensity over time in response to acute consumption of a high-fat diet. In addition, it is among the first to compare discounting rates, demand elasticity, and demand intensity between sedentary and endurance trained men.

Significant baseline differences were noted in discounting rates between sedentary and endurance trained, with sedentary individuals choosing more immediate choices and valuing the future less compared to the endurance trained individuals. Another study that investigated discounting rates in older adults (>60 years old) reported higher discounting rates for those who did not exercise, consistent with the results of our study.[26] These findings contribute to the evidence which suggests that exercise may influences discounting rates, as other studies have reported a decrease in discounting rates following an exercise intervention.[28]

Our findings indicate that discounting rates decreased over time in response to a controlled high-fat diet. Some have reported discounting rates remaining relatively stable over time,[19,39] and other studies have reported discounting rates decreasing over time in response to an exercise intervention,[28] yet the present study suggests that discounting rates are influenced by dietary changes. One hypothesis of why discounting rates decreased over time is that the controlled feeding diets consisted of foods that were different from subject's habitual consumption, suggesting that there could have been another influence on discounting rates over time. Another hypothesis is that the high-fat diet may have increased satiety, or created an

aversion to high-fat foods, which in theory could influence a decrease the reinforcing value of the high-fat foods and discounting rates, although hunger/liking and satiety were not measured.

In addition, this result contradicts what was recently discovered using rodent models. Rats fed a high-fat diet for 8 weeks, which consisted of 40% more kcals from fat than regular chow, preferred more immediate rewards.[30] After discontinuing the high-fat diet and resuming normal chow diet, the rats began to prefer the delayed reward more often, indicating that the high-fat diet induced impulsivity, although these results may not apply to humans.[30]

Measures of cognitive restraint, disinhibition, and hunger did not change significantly over time in response to dietary changes. This is also consistent with another study which investigated the effect of an exercise interventions on eating behaviors and reported no changes in measure.[40] Dietary restraint and disinhibition were not significantly correlated with discounting rates at baseline, in contrast to another study that reported more impulsive choices (i.e., choosing the immediate option more often) on a monetary DD task were correlated with higher disinhibition scores, and lower amount of immediate choices was correlated with and higher restraint, although this study had a larger sample size (n=56) and included men and women.[25] Although, there was a significant correlation between higher disinhibition scores with higher demand elasticity at baseline, indicating that the males in the study who were more susceptible to disinhibited eating, or eating in response to stimuli, were less reinforced by their favorite snack food of choice. In addition, higher hunger scores were correlated with higher demand intensity, meaning the more susceptible a person is to hunger symptoms, the more of their favorite snack food they would consume when it is free. Lastly, demand elasticity was positively related to dietary restraint, indicating that subjects who exhibited a higher tendency to restrict food intake purchased and consumed less of their favorite snack food. This result is

related to studies that have reported that higher cognitive restraint is related to less energy intake and dietary fat intake, although these results were reported in women.[41] Although, how cognitive restraint influences weight loss and BMI remains somewhat inconclusive.[42]

The present study has strengths and limitations. Strengths including having objective measures for exercise status, as indicated by maximal oxygen consumption tests, and having a controlled, standard-diet to standardize participant diets prior to the high-fat diet intervention. In addition, compliance to controlled feeding diets was determined by both subjective and objective measures.

Limitations include a sample size was small, which limited statistical power. A crossover design, consisting of 10 days of the STD followed by 5 days of a HFD compared to 10 days of a STD followed by another five days of STD, would have provided the ability to evaluate casual effects relative to a control condition, and if 55% kcals from fat is too much fat. In addition, an acute high-fat diet may not be a long enough period of time period to influence changes in demand elasticity, demand intensity, or eating behaviors. Also, both the DD task and the FPT were assessed using hypothetical rewards and hypothetical purchases, although previous research has reported that hypothetical rewards and actual rewards are discounted comparably, [43,44] and research using hypothetical and real purchases tasks of cigarettes reported similar results in quantifying purchasing behavior and demand.[45] The Food and Activity questionnaire might not be predictive of a participant's "favorite" snack food or sedentary activity since subjects have to choose from a limited list of foods/activities. Another consideration is that the FPT measures theoretical purchases at different prices and might not accurately reflect food reinforcement since participants do not have to work for access to food as in other studies,[46] and the FPT only assesses purchasing of one commodity when in real life, a person will allocate money to multiple

commodities.[11] Also, delay discounting includes many choice trials, and may be time consuming and difficult for people with short attention spans to answer, especially when assessed more than once.[35] Therefore, random answering may be problematic. Lastly, results only apply to young males. Additional research is needed to determine whether adherence to a high-fat influences discounting rates in other populations, such as females, or those who engage in difference types of exercise, and in other types of diets. Also, how exercise, discounting, and eating behaviors may interact and influence executive regions of the brain is needed further understand the cognitive processes that influence decision making.

CONCLUSION

Discounting rates were significantly different between sedentary and endurance trained men, with endurance trained men valuing future rewards more than sedentary men. This could possibly be related the effects of exercise on executive regions and reward centers in the brain (although not investigated in the present study), as previous studies have shown decreased activity in these regions when exposed to high calorie foods following exercise.[40,47] In addition, discounting rates significantly decreased over time in the full sample, indicating more value was placed on future rewards. Further research is warranted to understand how exercise influences discounting rates by investigating the activity of neuronal regions of the brain involved with discounting, such as the prefrontal cortex, and to determine causal effects of a dietary intervention on discounting by utilizing a crossover design.

FIGURES

Figure 1. Study Protocol Diagram

	Complete online screening
Session 1 Baseline Visit 1 **Time Point 1**	Informed Consent Health history questionnaire Godin PAQ Height/Weight Fasting blood draw Blood Pressure **Delay Discounting Task** **Food Purchase Task** **TFEQ**
Session 2 Baseline Visit 2	Return 4-day FIR Maximal Oxygen Consumption Treadmill Test DEXA
Sessions 3-12 Controlled Feeding Period 1 (10 days) Standard Diet	Weight Breakfast and Food Distribution Return previous cooler
Sessions 13-17 Controlled Feeding Period 2 (5 days) High-Fat Diet **Time Point 2 (S13)**	Weight Breakfast and Food Distribution Return previous cooler **Delayed Discounting Task** **Food Purchase Task** **TFEQ** **DEXA**
Session 18 **Time Point 3**	Weight Return previous cooler **Delayed Discounting Task** **Food Purchase Task** **TFEQ** **DEXA** Compensation

Figure 2. Participant Flow Diagram

Completed online questionnaire
(n=649)

n=330 declined participation
n=290 did not meet inclusion criteria

Session 1:
Baseline Visit 1
Time Point 1
(n=29)

Excluded (n=11)
- n=5 did not complete TP1 measures of DD, FPT, and TFEQ
- n=3 did not meet exercise criteria
- n=1 too high Block fat screener score
- n=1 female
- n=1 declined participant due to time commitment

Session 2:
Baseline Visit 2
(n=18)

Included in baseline analysis (n=17):
- n=5 sedentary
- n=12 endurance trained

Excluded (n=1)
- Too high habitual fat consumption
- Declined participation (n=6)

Sessions 3-12:
Controlled Feeding Period 1
(n=11)

Sessions 13-17:
Time Point 2 (S13) (n=11)
Controlled Feeding Period 2:
High-fat Diet
(n=10)

Excluded (n=1)
- Dropped out due to discomfort with study measures

Session 18:
Time Point 3
(n=10)

Sedentary
(n=3)

Endurance Trained (n=7)

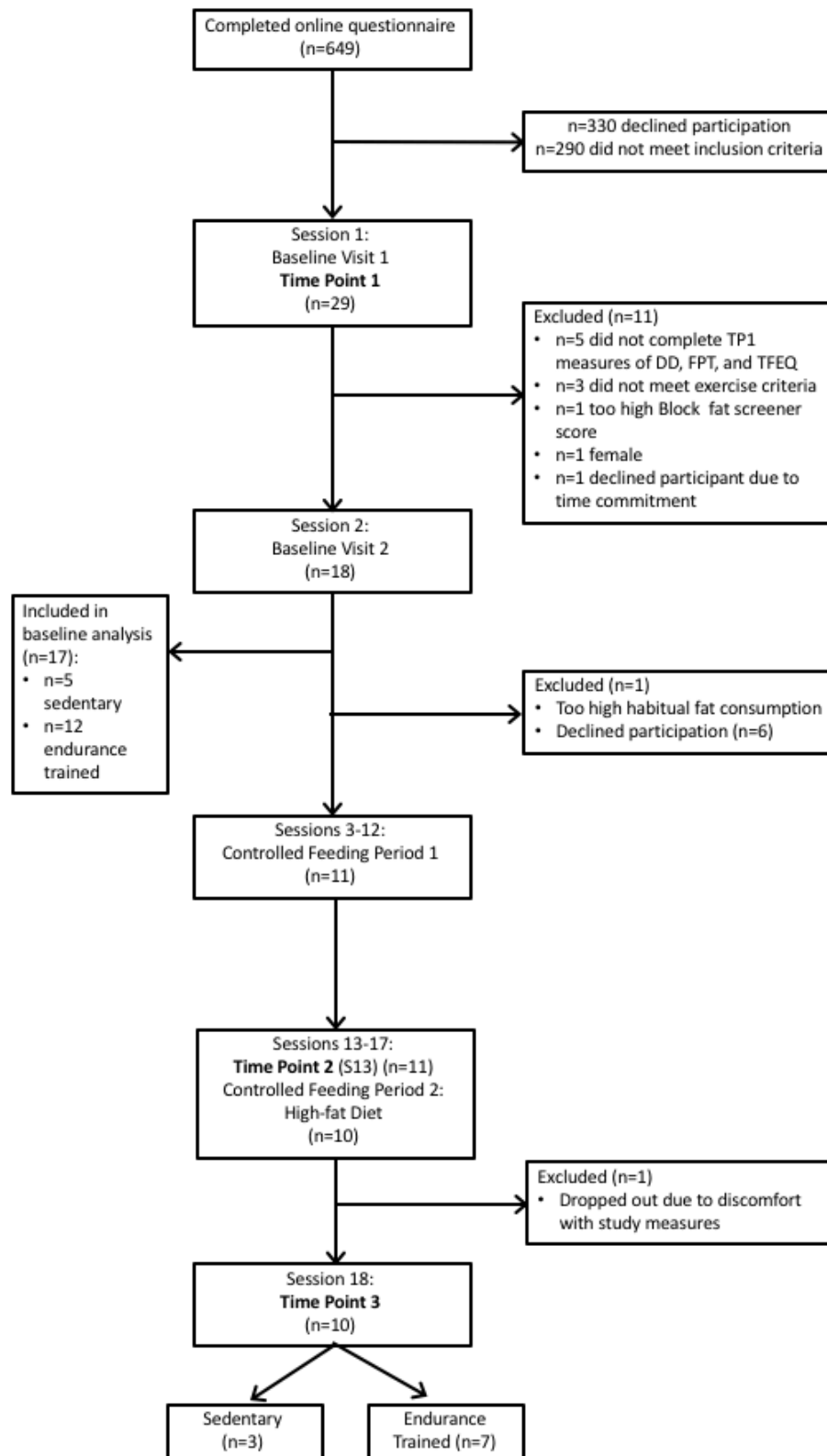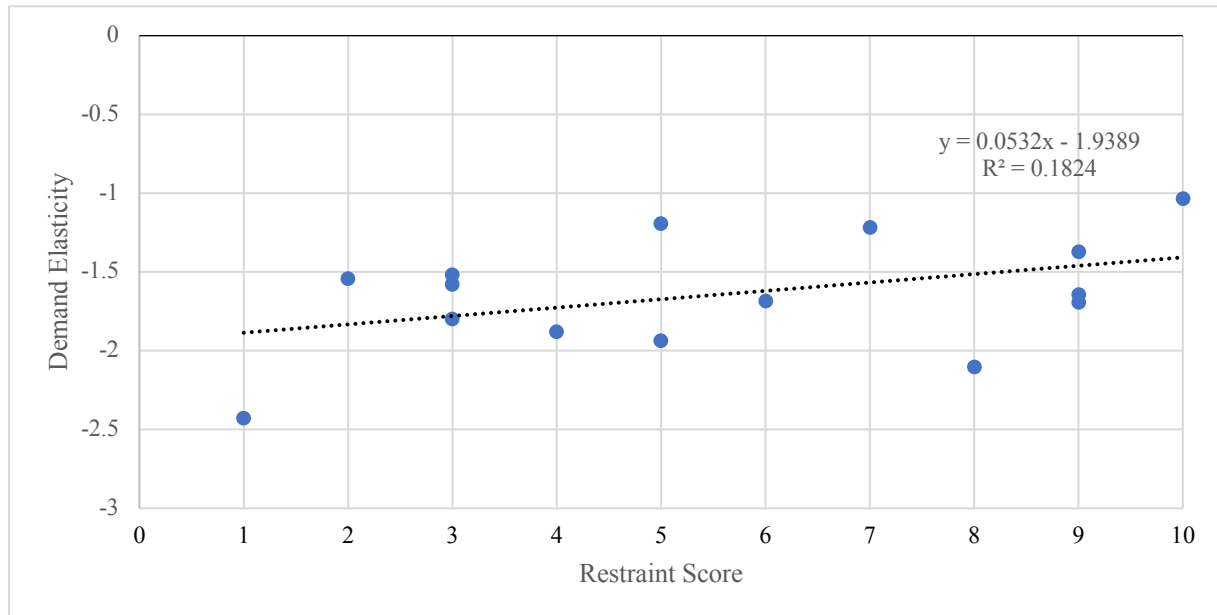**Figure 3.** Relationship Between Baseline (TP1) Cognitive Restraint and Demand Elasticity

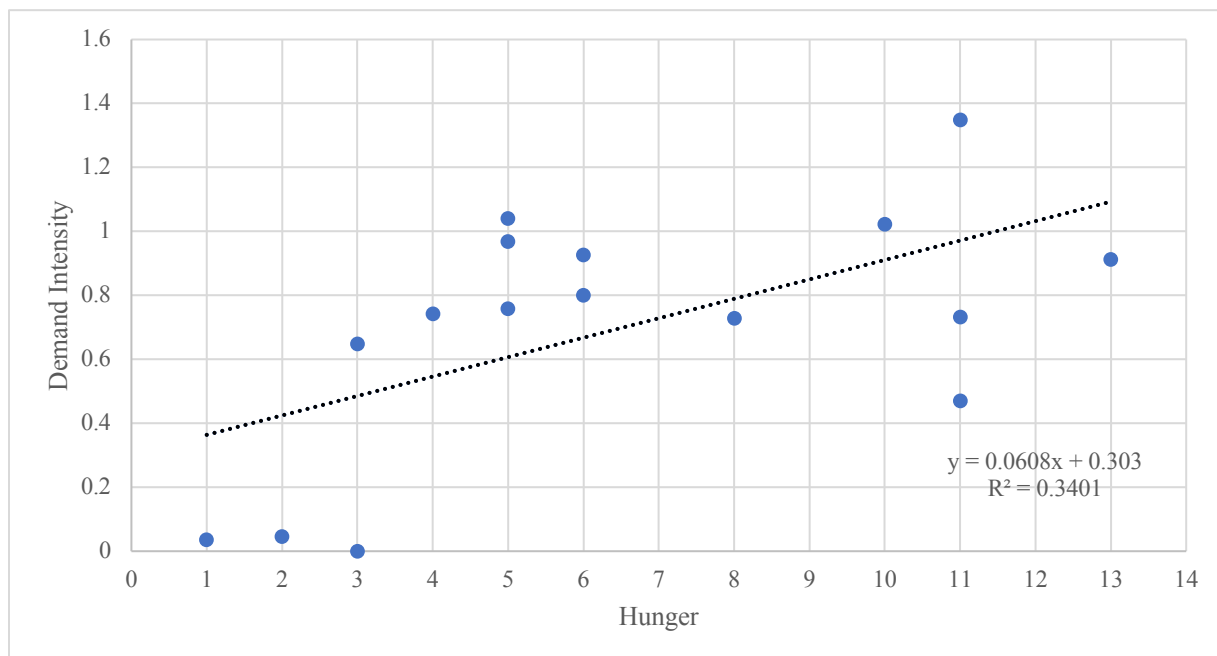**Figure 4.** Relationship Between Baseline (TP1) Hunger and Demand Intensity
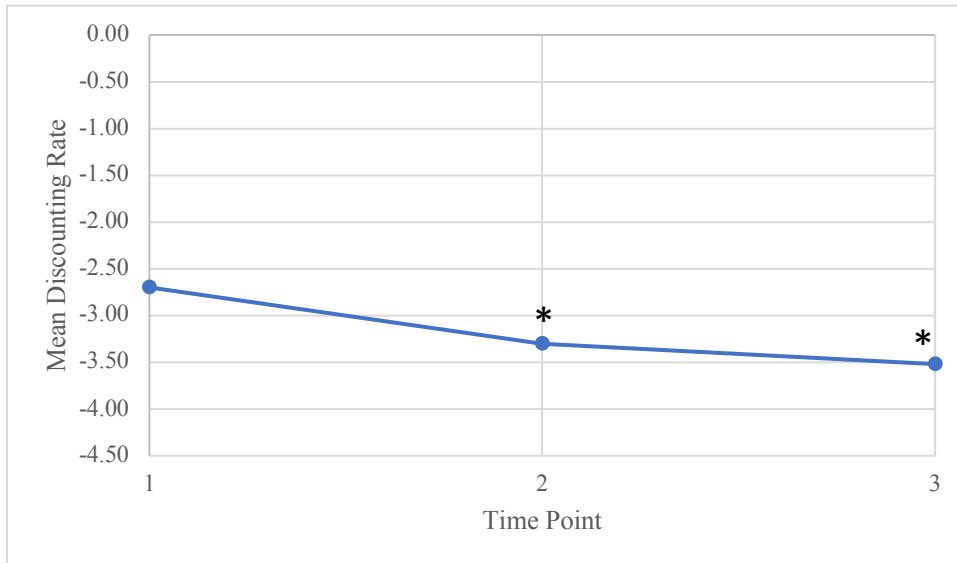
Figure 5. Discounting rates at baseline visit 1 (TP1), after standard diet/before high-fat diet (TP2), and after high-fat diet (TP3):

    a. In the full sample

*Significant differences (p<0.05) were found between TP1 and TP2, TP2 and TP3, and TP1 and TP3
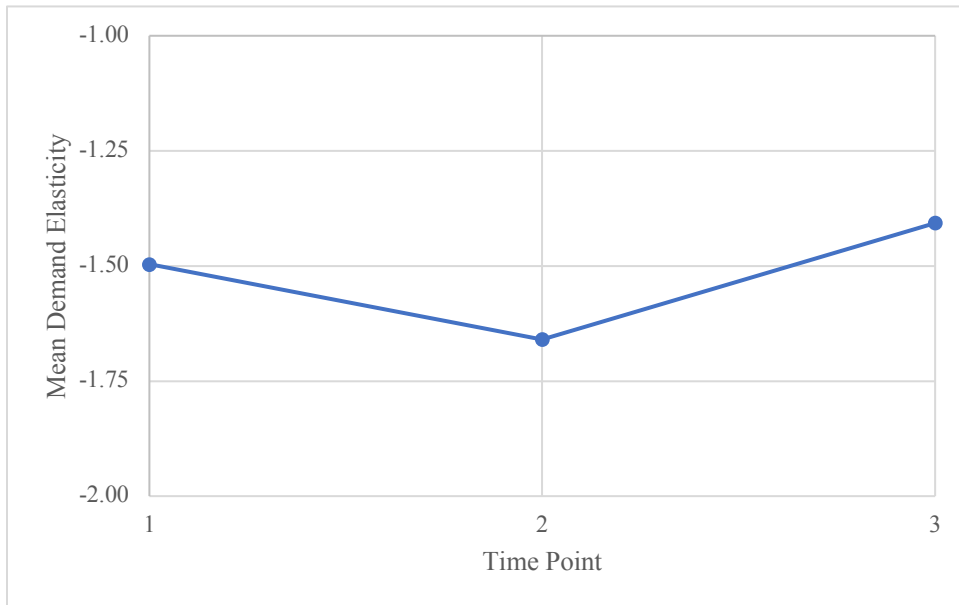
    b. By exercise group

*indicates significant difference between groups (p<0.05)

Figure 6. Demand Elasticity at baseline visit 1 (TP1), after standard diet/before high-fat diet (TP2), and after high-fat diet (TP3):

a. In the full sample

b. By exercise group

Figure 7. Demand intensity at baseline visit 1 (TP1), after standard diet/before high-fat diet (TP2), and after high-fat diet (TP3)

a. In the full sample

b. By exercise group
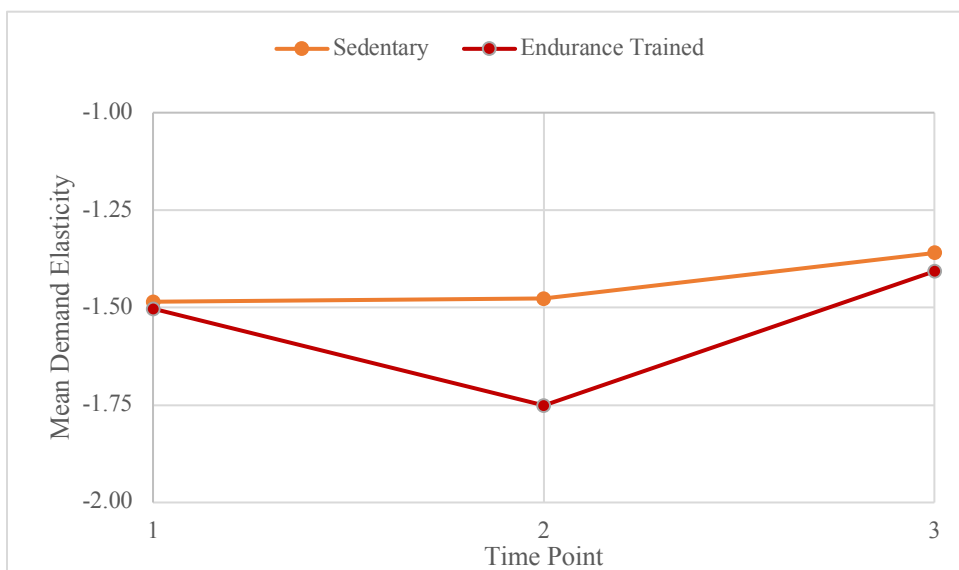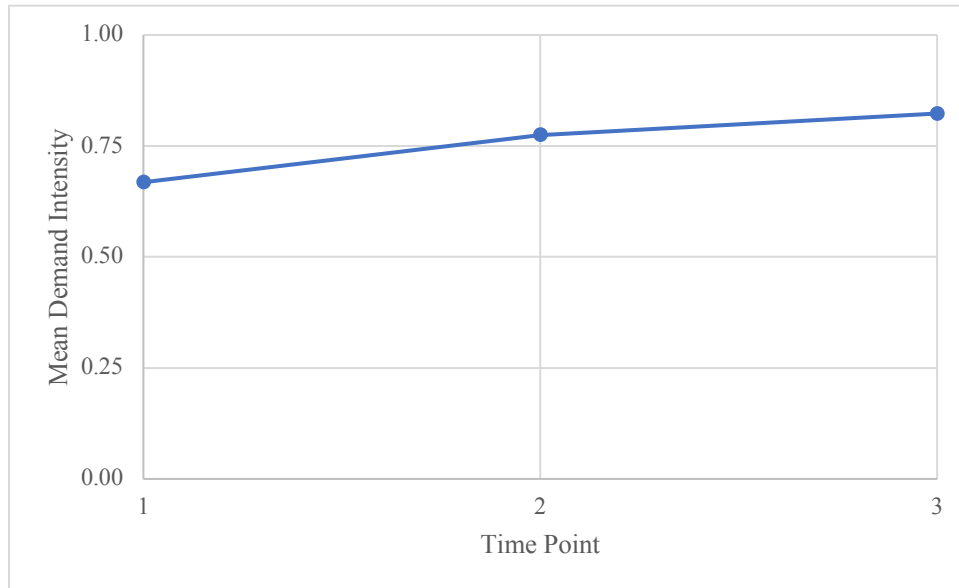
TABLES

Table 1. Participant characteristics

Participant Characteristics	Baseline Participants			Completed Participants		
	Sedentary (n=5)	Endurance Trained (n=12)	Total (n=17)	Sedentary (n=3)	Endurance Trained (n=7)	Total (n=10)
Age	26.2±5.1	22.5±3.6	23.6±4.3	27.7±6.5	22.1±2.1	23.8±4.4
Race/Ethnicity						
White, n (%)	4 (80)	9 (75)	13 (76.5)	2 (66.7)	6 (85.7)	8 (80)
Asian, n (%)	1 (20)	2 (16.7)	3 (17.6)	1 (33.3)	1 (14.3)	2 (20)
African American, n (%)	0 (0)	1 (8.3)	1 (5.9)	0 (0)	0 (0)	0 (0)
BMI, kg/m^2	24.9±3.0	23.0±1.9	23.5±2.3	23.4±3.0	23.4±2.1	23.4±2.2
Baseline weight, lbs	172.2±28.5	158.2±21.2	162.3±23.6	167.2±29.5	162.0±24.4	163±24.4
Body fat (%)	29.3±7.0	16.3±3.9**	20.4±7.9	25.6±6.3	17.3±4.4*	19.8±6.2
Fat Screener Score	25±10	21±9	23±9	33±5	21±7*	24±8
VO2Max (ml/kg/min)	38.6±5.2	57.1±7.4**	51.3±11.1	40.6±6.2	56.7±8.2*	51.9±10.7
Self-Reported Habitual Dietary Intake[a]						
Energy, kcals/d	2311±317	2867±927	2694±819	2219±408	2591±819	2479±718
Total fat, g/d	90.0±14.7	96.3±41.0	94.3±34.4	81.9±8.1	86.6±42.3	85.2±34.8
Total fat, % energy	34.5±3.7	28.8±6.2	30.6±6.0	32.9±2.9	28.3±7.8	29.7±6.9
Saturated fat, g/d	35.8±8.5	32.3±15.2	33.4±13.3	33.8±10.9	29.3±14.6	30.6±13.2
Saturated fat, % energy	15.5±7.2	9.7±3.0*	11.5±5.6	16.2±7.4	9.7±3.6	11.7±6.5
Carbohydrate, g/d	282.0±58.9	389.5±132.0	355.9±123.2	268.0±61.6	347.9±91.3	323.9±88.8
Carbohydrate, % energy	47.2±10.0	54.0±8.4	51.7±9.1	46.3±11.3	45.4±10.4	51.7±10.7
Protein, g/day	84.5±28.7	114.0±42.0	104.8±40.0	89.4±36.0	101.3±39.6	97.7±37.0
Protein, % energy	19.7±13.1	19.2±11.6	19.4±11.6	16.1±7.4	15.7±4.5	15.9±5.1
Sodium, mg/d	4556±567	4467±1477	4495±1242	4179±227	3920±1227	3998±1017
All values are expressed in mean±SD unless otherwise indicated						
* indicates significant difference between groups (p<0.05) ** indicates significant difference between groups (p<0.01)						
[a]missing habitual dietary intake data for one baseline participant as they did not complete baseline visit day 2 (n=11 endurance, n=16 total)						

Table 2. Weight Stability

	Wt. Day 1 of STD (lbs)	Wt. Post-STD; Day 1 of HFD (lbs)	Wt. Post-HFD (lbs)
All Completed Participants (n=10)	163.6±24.5	162.4±23.1	162.4±22.4
All values are expressed in mean±SD			
† indicates significant difference within group (p<0.05) ‡ indicates significant difference within group (p<0.01)			

Table 3. Differences in eating behaviors between activity groups

	Measure	Sedentary	Endurance Trained	Mean Difference
Cognitive Restraint	**TP1:** Baseline	5±3	5±3	0.3
	TP2: Post-STD	8±5	6±4	1.4
	TP3: Post-HFD	9±4	5±3	3.7
Disinhibition	**TP1:** Baseline	7±1	5±2	2.0
	TP2: Post-STD	6±2	6±3	0.8
	TP3: Post-HFD	5±2	5±2	0.7
Hunger	**TP1:** Baseline	7±3	6±4	0.8
	TP2: Post-STD	5±4	6±4	1.4
	TP3: Post-HFD	4±3	6±4	2.0
TP1: n=5 sedentary, n=12 endurance trained				
TP2: n=3 sedentary, n=8 endurance trained				
TP3: n=3 sedentary, n=6 endurance trained				
All values are expressed in mean±SD				
ᵃmissing values for 1 participant				
* indicates significant difference between groups (p<0.05) ** indicates significant difference between groups (p<0.01)				

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CHAPTER 3: Conclusions and Future Directions

In the current obesogenic environment, it is important to identify potential moderators of maladaptive behaviors, as choosing to live sedentary lifestyle is a risk factor for obesity and other diseases[1,2] Our results suggest that exercise may moderate discounting rates, as discounting was higher in sedentary men compared to endurance trained men, indicating that exercise may contribute to the increasing of the subjective value of delayed rewards, though how this occurs is unknown. Other studies with small sample sizes have reported significant decreases in discounting rates over time in response to an exercise intervention,[3] but additional studies are needed to determine the mechanisms of how exercise influences discounting, potentially by the utilization of neuroimaging techniques, such as function magnetic resonance imaging (fMRI). Also, additional research is needed to determine if different types of exercise, such as light or moderate physical activity, influence discounting, and to quantify how much exercise (e.g. time per day or week) is needed to have an effect on discounting. Lastly, many studies have reported greater discounting in women,[4] and future research is needed to investigate how discounting may be moderated in females depending on exercise status.

In the present study, discounting rates significantly decreased for the full sample following both controlled feeding diet phases: after 10 days of a standard diet, and after five days of a high-fat diet. We are unable to infer causal effects of diet on discounting, therefore future studies utilizing a crossover, controlled feeding design are needed. It is hypothesized that certain foods within the diets may have influenced discounting rates, as similar food items were used within both phases, or that there were other influences on discounting rates, such as increase satiety, which was not investigated in this study. Another hypothesis to why discounting rates decreased following the high-fat diet is that possible disliking of the high-fat foods may have

increased the value of healthy foods, although this was not studied. Lastly, it is hypothesized that the high percentage of fat in the diet may have created an aversion to high-fat foods, decreasing the motivation to obtain these foods, and which could have resulted in decreased discounting rates following the high-fat diet intervention. Therefore, future studies are warranted to determine the possible effects of certain foods on discounting as well as the effect that the reinforcing value of the high-fat foods may have on discounting. Also, hunger/liking of study foods and satiety measures could be obtained to determine if these variables have an influence on discounting. In addition, future studies with greater sample sizes are needed to improve statistical power.

Results from the current study could inform the development of interventions that aim to improve unhealthy eating behaviors and increase physical activity, as exercise and controlled feeding diets may influence a decrease in discounting, resulting in less impulsivity and greater valuation of future rewards. High discounting has been described as a trans-disease process, as discounting has been reported to be higher in those with drug addictions, substance abuse problems, and obesity.[5] Working memory interventions have been reported to decrease discounting rates in stimulant abuse users.[6] Future research could investigate how combining working memory and exercise interventions may influence unhealthy eating and activity behaviors, which may show profound effects on reducing maladaptive behaviors by increasing executive function in the brain.

Overall, future studies are needed to investigate how other types of exercise and specific food items may influence discounting rates in both genders. In addition, future studies are warranted to investigate the causal effects of diet on discounting, demand elasticity and intensity,

and eating behaviors by utilizing a crossover design and longer diet periods, as short-term diet

interventions may not influence these measures.

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APPENDIX A. Institutional Review Board Approval

VirginiaTech

MEMORANDUM

DATE: December 1, 2016

TO: Kevin Davy, Brenda Davy, Matthew Wade Hulver, Madlyn Irene Frisard, Jose Manuel Rivero, Elaina Lynn Marinik, Mary Elizabeth Baugh, Loren Ashley Weldon, Kristin Osterberg, Nabil E. Boutagy, et. al.

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Effect of High Fat Diet on Muscle Metabolism

IRB NUMBER: 06-367

Effective December 1, 2016, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the Amendment request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Full Review**
Protocol Approval Date: **October 14, 2016**
Protocol Expiration Date: **October 13, 2017**
Continuing Review Due Date*: **September 25, 2017**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

Date*	OSP Number	Sponsor	Grant Comparison Conducted?
03/06/2013	13012307	American Diabetes Association	Not required (Not federally funded)

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt. edu) immediately.