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Cognitive Control and Intertemporal Choice: The Role of Cognitive Control in Impulsive Decision Making

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COGNITIVE CONTROL AND INTERTEMPORAL CHOICE: THE ROLE OF COGNITIVE
CONTROL IN IMPULSIVE DECISION MAKING

Sarah Jean Getz

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Abstract

The purpose of this thesis is to examine the role of cognitive control mechanisms in intertemporal choice (ITC). Six experiments were conducted that were designed to characterize how a cognitive load affects control mechanisms and to investigate the function of these mechanisms in contexts known to facilitate decision-making processes that favor long-term rewards. Chapter 2 describes experiments that show that interference and/or fatigue of control mechanisms resulted in more impulsive ITC decisions. In Chapter 3, behavioral methods were used to compare and examine whether a working memory (WM) load fatigues or interferes with control mechanisms during ITC. Preferences for immediate rewards were examined in both high fatigue and high interference conditions. The results from these studies provided evidence to support the idea that interference with, rather than fatigue of, control mechanisms leads to decisions that are more shortsighted. In Experiment 5 (Chapter 4), a framing paradigm was used to examine whether greater patience is the result of recruitment of cognitive control processes when ITCs are framed as accelerated. Participants in this experiment responded to either delayed or accelerated intertemporal choices while under either a high or low WM load. Results from this experiment did not support the hypothesis that greater recruitment of control mechanisms underlies acceleration effects. Experiment 6 examined whether decreased discounting during future episodic thinking reflects greater exertion of control. A modified future episodic paradigm was used in this experiment, and participants completed intertemporal choices while under either high or low WM load. These results suggest that control does not underlie decreased discounting in future episodic thinking.

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Chapter 1: Literature Review and Background to the Thesis

Introduction

The focus of this thesis is on control processes in intertemporal choice. Intertemporal choice (ITC) involves trade-offs between costs and benefits at different points in time. ITC has important implications for personal finance, impulsivity, addiction, and other scenarios in which objectively superior long-term rewards are evaluated in light of subjectively superior short-term rewards. Selection of long-term rewards in ITC is hypothesized to require cognitive control or the ability to guide attention, thought, and action in accordance with goals or intentions (Miller & Cohen, 2001). One of the most salient features of cognitive control is that it is a limited capacity resource. Frequently, decisions are made in an ITC framework while tasks that also require cognitive control are simultaneously performed, which can cause interference and/ or fatigue of control mechanisms necessary for the selection of long-term rewards. This interference/ fatigue may lead to decisions that are impulsive, maladaptive, or suboptimal. Likewise, it may be the case that greater patience in some decision-making contexts is the result of greater exertion of control. Given this, the aims of this thesis are: (1) to characterize how a cognitive load affects control mechanisms in ITC; and (2) to investigate the role of control mechanisms in contexts known to facilitate decision-making processes that favor long-term rewards.

In order to examine the role of cognitive control mechanisms in temporal decision making processes, three related goals will be pursued: (1) examination of the role of control in intertemporal choice by taxing control mechanisms with a working memory load; (2) characterizing whether it is fatigue or interference of control mechanisms that leads to greater

impulsivity; and (3) examining what the role of control is in paradigms in which participants behave more patiently. Included in this introduction is a review of relevant literature from behavioral economics, psychology, and cognitive neuroscience. Following this literature review is an outline of the experiments conducted for the thesis.

Review of the Literature

Normative and descriptive models of Intertemporal Choice

Temporal discounting refers to the human tendency to discount the present subjective value of a reward as a function of the delay to actually receiving it. Traditional economic models of temporal discounting have proposed that delayed rewards are discounted at a constant rate over time (Fisher, 1930; Samuelson, 1937). The Discount Utility (DU) model is a normative model, which takes the form:

$$U = x\delta^t$$

In the DU model, a reward with a utility x is discounted by the parameter δ , which treats a given reward equally regardless of when it occurs. The DU model has dominated economists' theoretical models over the past 80 years and implies a rational claim that if a reward is worth 10 percent less when delayed by one year, then it should be worth an additional 10 percent less when delayed by an additional year, and so on (Frederick et al., 2002).

In contrast to normative models of discounting, psychologists and behavioral economists have found that empirical data indicates that a hyperbolic function more accurately captures human discounting behavior. In an early descriptive model, Herrnstein's "matching law" asserted that when expending time or effort between two sources of rewards, the allocation of

effort is proportionate to the size and rate of the reward and inversely proportion to the length of the delay (Herrnstein, 1974). Hyperbolic discounting was implicit in Herrnstein's law. In his research on intertemporal choice with pigeons, psychiatrist George Ainslie observed preference reversals for earlier rewards when the "smaller sooner" and "larger later" rewards were moved earlier in time (Ainslie & Haslam, 1992). Specifically, Ainslie observed that when choosing between a smaller reward sooner and a larger reward later, pigeons discounted the value of the later reward by a factor that increased with the length of the delay. The pattern followed a hyperbola, such that, after a given threshold of time, the devaluing effects of the delay decreased.

The hyperbolic discounting model therefore captures the observed tendency of people to discount more steeply over the short term versus the longer term. The model takes the following form:

$$V = \frac{A}{1 + kD}$$

In the hyperbolic discounting model, V is the subjective value, A is amount of the future reward, D is the length of the delay, and k is the discounting parameter, which describes the rate at which subjective values decrease over time (Mazur, 1987). A higher k value indicates greater impulsivity and an unwillingness to wait for larger future rewards. Conversely, a lower k value indicates greater relative patience and a willingness to wait longer for rewards. ITCs that are biased toward short-term rewards are considered impulsive and correspond with higher k values, as choosing the smaller, more immediate reward would result in less overall gains being earned (Green et al., 1999; Kirby & Herrnstein, 1995). The hyperbolic model is typically favored over exponential models because it fits well to most data sets and accounts for preference reversals or dynamic inconsistencies (Strotz, 1955). To demonstrate preference reversals, Strotz and Thaler both use an example in which one imagines that they are choosing between one apple today or

two apples tomorrow. Then they are then presented with a second example choice of one apple in one year or two apples in one year plus one day. While some may be tempted to select one apple today in the first example, almost no one would choose one apple in one year in the second example. If decision makers were exponential discounters as normative models predict, they would not show preference reversals (Thaler, 1981; Thaler & Shefrin, 1981).

More recent research has suggested that an additional parameter might best capture human temporal discounting. In an extension of exponential discounting, Laibson's quasi-hyperbolic model, derived from work done by Phelps and Pollak (1968), introduced the parameter β , an additional parameter that specifically weighs the immediate reward (Laibson, 1997). In Laibson's model, the discounted value of a reward U received at delay t is equal to $U\beta\delta^t$, where β and δ are constants between 0 and 1, and δ is the discount rate in the standard exponential formula.

Neuroimaging of Intertemporal Choice

In an early functional magnetic resonance imaging (fMRI) investigation of ITC, McClure et al. (2004) asked participants to answer monetary choices that varied in delay to delivery while in the fMRI scanner. In line with David Laibson's (1997) $\beta - \delta$ model of intertemporal choice, McClure et al. predicted that separable neural systems would be recruited when an immediate reward was offered.

McClure et al. found that, as predicted, limbic structures associated with reward processing (including the striatum and ventral medial prefrontal cortex [vmPFC]) responded preferentially to rewards that were immediately available. Areas involved in higher order cognitive control, including the dorsolateral prefrontal cortex (dlPFC) and right posterior parietal

cortex (PPar) were active during all choices (see also Cohen et al., 1997; Duncan & Owen, 2000; Miller & Cohen, 2001). Importantly, when only choices involving immediate options were examined, the interaction between limbic reward regions and prefrontal control regions predicted choice outcome, with greater later choices corresponding to greater activity in prefrontal regions. Regions that responded to immediately available rewards were labeled the β network, whereas regions active during all choices were labeled the δ network.

In a subsequent investigation by McClure et al. (2007), it was again observed that the beta and delta networks were similarly activated for choices involving primary rewards offered over shorter time intervals. Importantly, in both investigations conducted by the researchers, the relative activation of the two systems predicted choice outcomes, with greater activity in regions comprising the delta network corresponding with greater choices for later rewards. The pattern of activity observed in the delta system was consistent with the role of this system in exerting control to produce patient long-term decisions.

In contrast to the dual valuation model that McClure et al. (2007) proposed, Kable and Glimcher (2007) have suggested that a single neural system encodes the value of all rewards irrespective of their delay. The regions identified by Kable and Glimcher included a similar network of regions as those identified by McClure et al. (e.g., vmPFC, dlPFC and PPar). However, due to methodological differences, a direct comparison between the findings is difficult.

The role of dlPFC

Hare, Camerer, and Rangel (2009) found that among dieters categorized as “self-controllers” or “non-self-controllers,” dlPFC modulated vmPFC activity only when “self-controllers” successfully exerted control in decisions about healthy and good tasting foods (Hare,

Camerer & Rangel, 2009). These results were consistent with other theories of the role of dlPFC in self-control and decision making processes; namely, that dlPFC sends bias signals to other brain regions in the service of task-relevant processing and the suppression of irrelevant activity (Miller and Cohen, 2001).

The hypothesis that dlPFC has a role in the controlled selection of delayed rewards was strengthened by Figner et al. (2010), who applied repetitive transcranial magnetic stimulation (rTMS) to dlPFC during an intertemporal choice task. When rTMS was applied to left dlPFC rather than right dlPFC, participants chose immediate options significantly more often. RTMS did not affect judgments in a separate valuation task, which suggests that the role of dlPFC may not be central to valuation but is potentially central in modulating value signals encoded in other regions, such as ventromedial prefrontal cortex (vmPFC), in order to exercise self-control.

Current work

The role of dlPFC in ITC may be to bias processing in favor of choosing the larger-but-later over the smaller-but-sooner reward. This hypothesis has its basis in neuroimaging evidence showing correlations between activity in dlPFC and patient ITC decisions (McClure et al., 2004; 2007), dlPFC activity and the degree of self-control in dieters (Hare, et al., 2009), and rTMS evidence that links disruption of dlPFC activity with impulsive ITC decisions (Figner et al., 2010). This hypothesis is also informed by a dual-process theory in the judgment and decision making literature in which cognitive processes that are rapid and automatic (system 1) are in conflict with those that are slow and deliberative (system 2; Kahneman & Frederick, 2002, Stanovich & West, 2000).

DL PFC is also sensitive to higher working memory (WM) loads in the N-Back task and is thought to have a role in active maintenance of task relevant context (e.g., goals) information

in WM (Cohen et al., 1997; Miller & Cohen, 2001). Therefore, the effect of a cognitive load during ITC may be that dlPFC cannot mediate bias signals needed in the controlled selection of delayed rewards while actively maintaining more substantial WM representations. Given the evidence for the role of dlPFC in exerting control to support long-term decisions, then it follows that interfering with or fatiguing cognitive control mechanisms during ITCs with a high WM load should lead to more impulsive choices. This hypothesis has its basis in the role of dlPFC in cognitive control and in the limited capacity of cognitive control (Carter & van Veen, 2007; Miller & Cohen, 2001).

Overview of the Thesis Experiments

The experiments in this thesis examine the effects of a WM load on intertemporal choice behavior. Specifically, this thesis: (1) examines if a high working memory load leads to greater impulsivity; (2) characterizes whether fatigue or interference of control mechanisms leads to greater impulsivity; and (3) examines the role of control mechanisms in paradigms in which participants behave more patiently. The following section details the rationale, design and key predictions of each of the experiments.

In chapter 2, Experiment 1 seeks to address the concerns of previous researchers about erratic responding while participants answer ITCs under a working memory load (Franco-Watkins et al., 2006; 2010). Specifically, in Experiment 1, after determining a baseline estimate of each participant's individual discount rate (or k value) without a WM load, ITCs will be subsequently presented above and below each participant's indifference point and are interleaved with either a high or a low WM load. It is predicted that: (1) participants will show greater impulsivity under a higher working memory load; and (2) if participants respond lawfully and

non-randomly, then a significant linear trend will be observed about indifference points for both high and low load conditions.

Experiment 2 is designed to examine whether discount rates increase under high WM load as compared to low WM load. Intertemporal choices will be dynamically adapted in Experiment 2 based on choice behavior so that choices are always presented at the indifference point. It is predicted that the increase in participants' discount rates will be greater in the high WM load condition as compared to the low WM load condition.

In chapter 3, the goal of Experiments 3 and 4 is to determine the effects of a cognitive load on cognitive control mechanisms in ITC by specifically investigating if a working memory load fatigues or interferes with cognitive control mechanisms in ITC. By manipulating both the number of trials and the size of the working memory load, Experiments 3 and 4 will examine whether fatigue (i.e., the number of trials) and/or interference (i.e., size of the working memory load) will lead to greater preferences for immediate rewards. Three possible outcomes are hypothesized: either 1) the high interference group; 2) the high fatigue group; or 3) both the high interference and high fatigue groups will select the immediate option more often than the delayed option as compared to the low interference and fatigue groups.

In chapter 4, Experiment 5 is designed to examine the role of control in acceleration effects. Specifically, the purpose of Experiment 5 is to examine if decreased discounting observed in acceleration framing is the result of greater exertion of cognitive control. A 2 x 2 between subjects factorial design will be used to examine the effects of framing (either delay or acceleration) and WM load (either high or low) on discount rates. Based on the hypothesis that cognitive control is necessary to shift decisions toward greater patience, it is predicted that a high WM load will attenuate acceleration effects.

Experiment 6 examines the role of control in future episodic thinking. Specifically, this experiment examines if decreased discounting is the result of heightened cognitive control when choices are tagged with participant-specific future events. A 2 x 2 between subjects factorial design will be used to examine the effects of episodic tag (either control or episodic) and WM load (either high or low) on the percentage of impulsive choices for immediate rewards. This experiment is based on previous findings that the degree of discounting is inversely related to the degree of future oriented thinking and recruitment of control mechanisms. If control mechanisms underlie decreased discounting during future episodic thinking, it is predicted that a high WM load will attenuate this reduction in discounting.

Chapter 2: Cognitive Load and Intertemporal Choice

Introduction

As introduced in Chapter 1, it is hypothesized here that the regions that comprise the delta system are responsible for patient temporal decisions and that disruption of those mechanisms leads to more impulsive temporal decisions. The two experiments in this chapter examine the effects of a working memory load on control mechanisms in ITC. Experiment 1 will address previous confounds in this area of research and examine whether a working memory load disrupts ITC control mechanisms. Experiments 2 will employ a novel procedure to address methodological concerns raised in Experiment 1.

Experiment 1

Previous investigations of the effects of a WM load on intertemporal choices have been met with skepticism, as it has been difficult to dissociate impulsive from erratic responding, due to factors such as distraction, in an ITC task (Franco-Watkins, Pashler & Rickard, 2006; Franco-Watkins, Rickard & Pashler, 2010). In a study conducted by Hinson and colleagues (2003), participants were asked to complete ITC decisions before recalling a digit from a previously encoded digit string (digit memory condition). Participants exhibited higher k values, and thusly greater impulsivity, in this digit memory condition than in a control condition in which participants simply entered a digit that appeared on the screen (Franco-Watkins, Pashler & Rickard, 2006).

In the Hinson et al. control condition, which was intended to provide a baseline estimate of ITC preferences, participants chose earlier rewards in only 25% of trials. Therefore in the digit memory condition, random responding (i.e., choosing earlier rewards on 50% of trials) would

automatically result in comparatively more choices for earlier rewards. Consequently, by design, the digit memory condition yielded more choices for sooner rewards and thus higher k values, suggesting greater impulsivity as compared to the control condition. The claim that the digit memory manipulation led to greater impulsivity was contested on the basis that erratic or random responding had been confounded with impulsive responding (Franco-Watkins et al., 2006; 2010). A proper test to reconcile this would be to impose WM load after determining participants' baseline k values.

In Experiment 1, we sought to address the limitations discussed above by first estimating participant specific discount parameters using a titration procedure. Individuals' choices were used to derive the participant-specific discount rate using a simple hyperbolic function as described in Chapter 1. During titration, choices were presented that dynamically converged on the participants' indifference point. The "indifference point" is the k -value at which both the smaller sooner and larger later options would be equally preferred (referred to as "baseline k " throughout). The titration method allowed us to address previous concerns about erratic responding (Franco-Watkins et al., 2006; 2010) and provided a baseline estimate of each participant's individual k value without a WM load. This final k was used as the baseline "indifference point" for the subsequent intertemporal choice task.

After the initial titration to determine baseline k , intertemporal choices were subsequently presented above and below each participant's baseline k (referred to as " k_{choice} range" throughout). Intertemporal choices were also interleaved with either a high or a low WM load. It was hypothesized that if participants responded lawfully and non-randomly, then a significant linear trend should be observed about baseline k values for both high load (HL) and low load (LL) conditions. In other words, an effect of WM load on choices for earlier rewards should be

reflected by a main effect on WM load and k_{choice} range, but that there should be no interaction between these factors (Figure 2).

Materials and Methods

Participants. Eighty-eight undergraduates at Princeton University (45 females, ages 18 -21) participated. The Institutional Review Board at Princeton University approved this study. All subjects provided written, informed consent prior to participation.

Apparatus and Materials. ITC trials consisted of two monetary options, “immediate” and “delayed,” or “later”. The immediate option always had a lower undiscounted value than the delayed option. Delays for the later option varied across trials with a range of one to eight weeks. Both earlier and later reward amounts varied from \$5 to \$40. The presentations of the immediate and delayed options were counterbalanced between the left and right side of the computer screen. Participants were allotted unlimited time to respond to ITC questions. At the end of the experiment, one of the ITC trials was randomly selected for remuneration. Participants received the reward selected immediately in cash; however, they were not informed until after the study that cash payments would actually be immediate.

WM load was manipulated using two variants of the N-Back task, which consisted of a continuous stream of letter stimuli, presented one at a time interleaved with ITC trials. Stimuli consisted of eight phonologically distinct letters (*B, F, K, H, M, Q, R, X*) and were randomly presented in either upper or lower case. Participants in the 3-Back (high load/ HL) condition assessed whether the current stimulus matched the stimulus three trials ago. Participants in the 0-Back (low load/ LL) condition assessed whether or not the current letter was the letter *M*. In both the high and low load groups, a single block consisted of 49 trials. Letters were presented

centered on the screen for 500 ms, and participants were instructed to respond as quickly and accurately as possible.

Design. Participants were randomly assigned to either the high load condition ($n = 44$) or the low load condition ($n = 44$). The experiment began with a block of twenty titration ITC trials (without N-Back) to determine baseline k . K values were derived using the simple hyperbolic function:

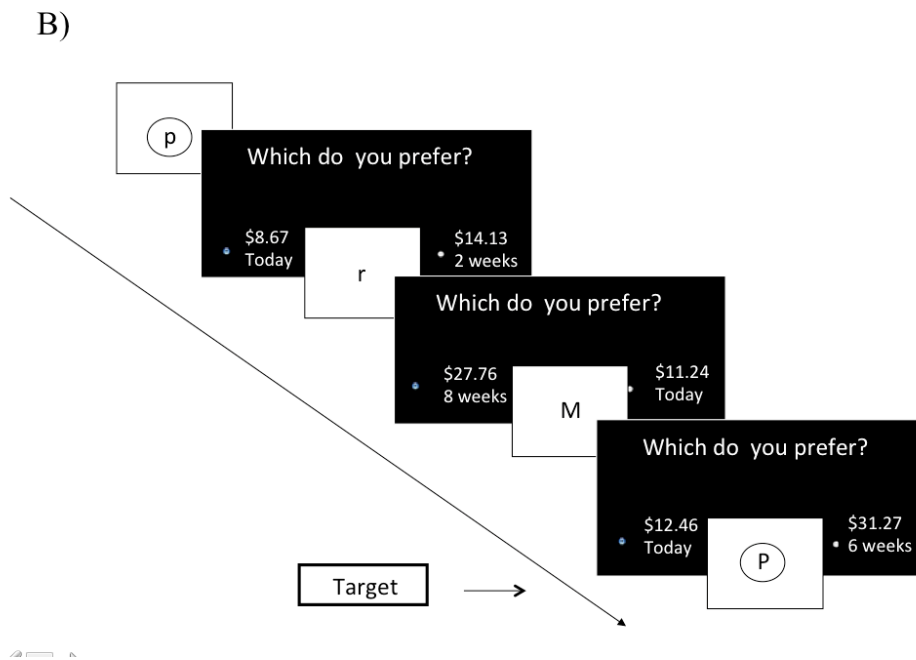
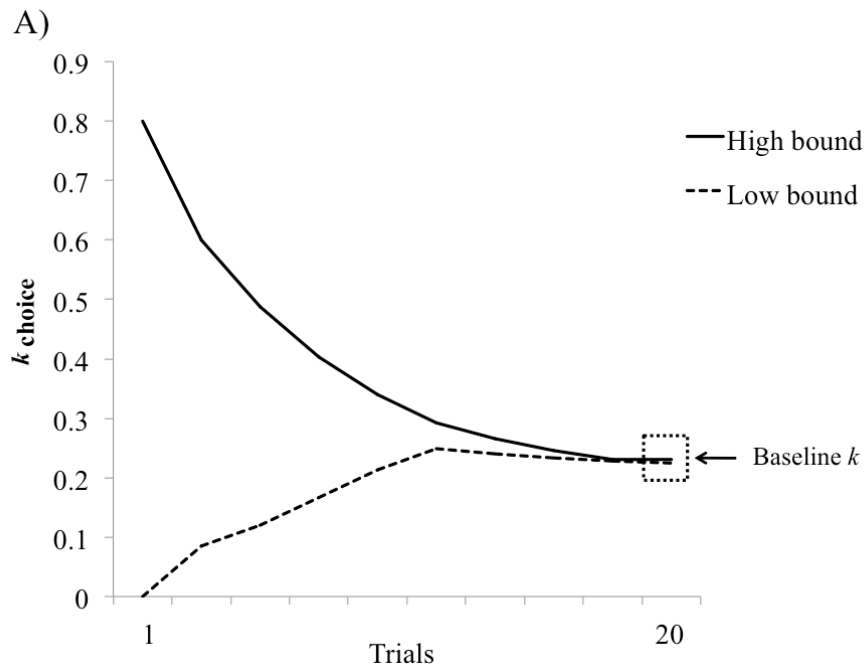
$$V = \frac{A}{1 + Dk}$$

Where V = time discounted value (i.e., “present value”) of a delayed amount, A = amount, D = specified delay (in days), and k was a fit parameter (Mazur, 1987).

Baseline k was estimated during the first 20 trials by successively probing whether the participant’s k value was between two bounds, the initial values of which were set to 0 (no discounting) and 0.8 (very high discounting). Choices were generated using one of the two alternating bounds, and the bounds were adjusted according to the participant’s answers. If the participant picked the long-term option when the high bound was tested, the tested value was assumed to be too large and was adjusted to a lower value. For example, if the choice offered was, “Which do you prefer: \$11.58 today or \$85.69 in 8 weeks?” and “\$85.69” was selected, the next choice for the high bound was given a smaller k_{choice} value. Similarly, if the participant picked the short-term option when the lower bound was being tested, it was assumed to be too small and was adjusted to a larger value. For example, if the choice offered was, “Which do you prefer: \$14.34 today or \$18.64 in 2 weeks?” and “\$14.34” was selected, the next choice for the low bound had a greater k_{choice} value. The bounds converged to encompass a small interval

containing the participant's estimated baseline k . The two bounds were averaged after 20 trials (Figure 1a).

Following the first 20 trials, participants then performed 98 ITC trials interleaved with N-Back, high WM load (3-Back; Figure 1b), or low WM load (0-Back; Figure 1c). For the ITC questions, choices were generated using seven different k_{choice} values. Three were below participant's estimated baseline k , one was at baseline k , and three were above baseline k (0.78 k , 0.85 k , 0.93 k , 1 k , 1.08 k , 1.15 k and 1.23 k) (we refer to this independent variable as the " k_{choice} range" throughout). The k_{choice} range variable was utilized in order to detect random responses. If participants responded lawfully (i.e., not randomly) to choices, then it was believed that their choices would show a significant linear trend about their baseline k . In this case, it was believed that participants would choose the early option progressively more often as choices fell below baseline k and would choose the delayed option progressively more often as choices exceeded baseline k (as depicted in Figure 2). If participants responded randomly to ITC questions, there should be no relationship between their choices for earlier and later rewards and the k_{choice} value used to generate each question.



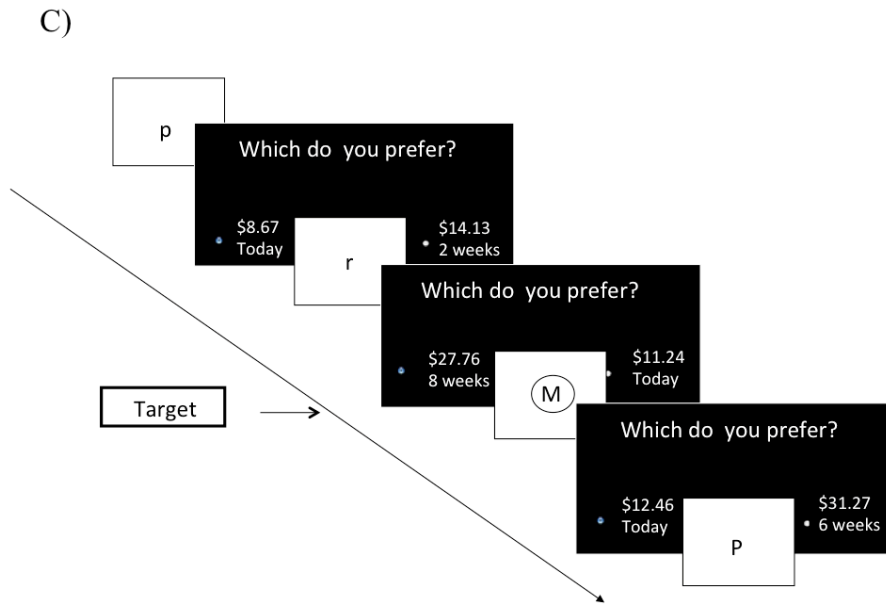


Figure 1. Procedure: Titration trials and ITC tasks. *A)* Titration trials: Discount parameters were estimated during the first 20 trials by successively probing whether the participant's k value was between two bounds, the initial values of which were set to zero (no discounting; hatched line) and 0.8 (very high discounting; solid line). ITCs were generated using one of the bounds (the bound used alternated between probes), and the bounds were adjusted according to the participant's answers. The bounds converged and were averaged to encompass a small interval containing the participant's baseline k . *B)* Task design for the high load condition. *C)* Task design for the low load condition.

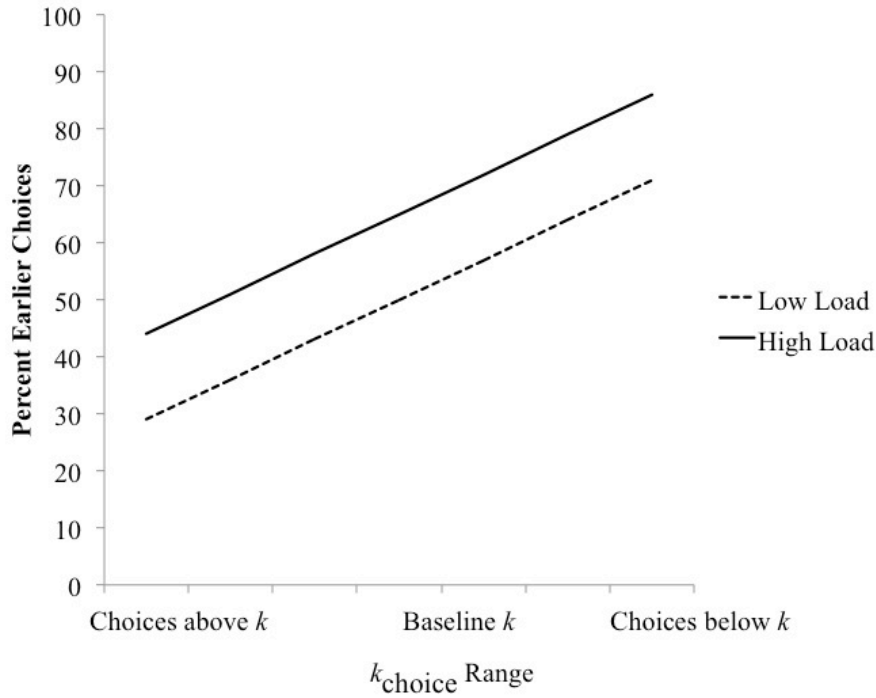


Figure 2. Predictions: A main effect of WM load and k_{choice} range, and no interaction.

Results

N-Back

Mean N-Back accuracy was 98% for the low load group and 77% for the high load group. All trials (both incorrect and correct) are included in the analyses presented below.

Effects of WM load

The three main predictions were: 1) the high load group would choose earlier rewards more often than participants in the low load group (a main effect of WM load), 2) there would be a lawful and non-random pattern of responses to choices with respect to the k_{choice} range, and 3) there would be no interaction between WM load and k_{choice} range.

A two (load) by seven (k_{choice} range) ANOVA was conducted, with the proportion of choices for the earlier reward as the dependent variable. The first prediction was supported by a significant main effect of WM load ($F(1,85) = 4.43, p < .05$) such that participants in the high

WM load condition chose the earlier reward more often than participants in low WM load condition. The second prediction was supported by a significant main effect of k_{choice} range, $F(4.26, 362.17) = 21.06, p < .001$ (Figure 3), suggesting that participants did not respond randomly, but rather showed consistent responses with respect to the discounted value of the options.

The absence of an interaction ($F(4.26, 362.17) = .81, p = .60$) between load and k_{choice} range further suggested that participants responded lawfully and non-randomly, supporting the third prediction. To ensure that participants responded lawfully in both load conditions, we conducted two separate one-way repeated measure ANOVAs for each group. Both revealed a significant main effect of k_{choice} range for the high load ($F(3.50, 147.23) = 11.71, p < .001$) and low load groups ($F(6, 258) = 9.87, p < .001$). This effect was further bolstered by significant linear trends in both the high load ($F_{Linear}(1,42) = 24.91, p < .001$) and low load groups ($F_{Linear}(1,43) = 29.80, p < .001$). These significant linear trends, coupled with the absence of an interaction between load and k_{choice} range, indicated that participants responded lawfully to choices as a function of their baseline k values.

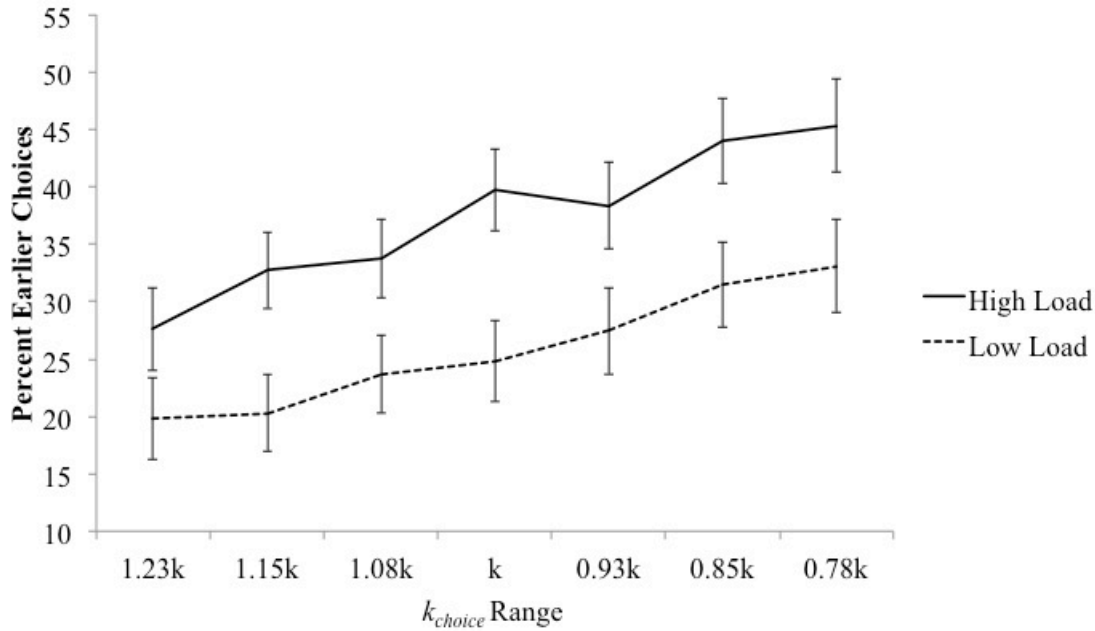


Figure 3. Percent choices for earlier rewards for high load and low load groups as a function of k_{choice} range. Error bars indicate one standard error above and below the mean.

Experiment 1 Discussion

These results were consistent with the hypothesis that a high WM load either interferes with or fatigues control mechanisms needed for patient decision making in ITC. This observation is in line with neurobiological models discussed in Chapter 1 that suggest that increased engagement of prefrontal control regions predicts choices for later outcomes (McClure et al., 2004; 2007), is necessary for patient decisions when an immediate reward is offered (Figner et al., 2010), and has a role in self-control (Hare et al., 2009).

These results are also consistent with previous work that suggests WM load leads to more impulsive decision-making in an ITC task (Hinson et al., 2003) and address concerns about the effects of WM load on ITC behavior (Franco-Watkins et al., 2006; 2010). Specifically, choice

behavior in the high load condition remained lawful with respect to questions presented above and below each participant's baseline k , indicating that WM load caused more impulsive, rather than random, behavior.

We predicted that participants would be indifferent between sooner versus later choices for choices presented at baseline k . Our results did not support this claim, however, as the sooner option was chosen on average in 31% of trials by the low load group and in 38% of trials for high load group. One possibility is that participants' k values drifted toward greater patience from the baseline k values estimated during initial titration over the course of the experiment. This possibility is addressed in Experiment 2 by dynamically adapting choices to participants' discounting behavior throughout the experiment.

Experiment 2

In the previous experiment, participants' baseline k values were estimated during the initial titration trials. After titration, the three types of choices described in Experiment 1 were presented: 1) below the participants' baseline k , 2) equivalent to the participants' baseline k , and 3) above the participants' baseline k . When k_{choice} was equivalent to the participant's baseline k , or indifference point, the participant was assumed to be subjectively indifferent about the immediate versus later options. In other words, it was predicted that choices for early and later rewards would be equivalent, or 50% for both early and later options. However, our results indicated that when choices were presented at the indifference point, the earlier reward was chosen on average in 31% of trials by the low load group and in 38% of trials for high load group. Therefore, participants were not indifferent about choices at their baseline k . One possible account for this is that participants' discounting behavior changed from their baseline k , with a

tendency toward greater patience, with repeated administration of choices. Therefore, Experiment 2 was designed to address this possibility by adapting choices throughout the task so that the questions changed corresponding to changes in the participants' underlying discounting behavior over the course of the task. More specifically, ITC questions were continually adapted based on participants' choice for the early or later reward in the previous questions.

As in the previous experiment, it was hypothesized in Experiment 2 that a high WM load would lead to greater impulsivity as compared to low WM load. Experiment 2 had two major aims: (1) to replicate the findings of the first experiment by demonstrating that a high WM load leads to greater discounting; and (2) to maintain choices for earlier options at 50% by adapting k_{choice} values based on participants' choices for the early or later reward in previous ITC questions.

K_{choice} values were adjusted based on participant's choice for the earlier or later option in the previous question. K_{choice} increased when the earlier reward was selected in the previous choice and decreased when the later reward was selected in the previous choice. In line with our predictions, it was anticipated that the increase in participants' k values under high load would be reflected in greater change in k_{choice} values in the high WM load condition as compared to the low WM load condition.

Materials and Methods

Participants. Fifty-four undergraduates (29 females, ages 18-21) at Princeton University participated. The Institutional Review Board at Princeton University approved this study. All subjects provided written, informed consent prior to participation.

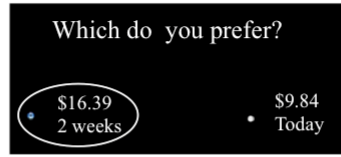
Apparatus and Materials. The ITC and N-Back trials had identical format as described above in Experiment 1.

Design. A within subjects manipulation of WM load was used. The order of the high load (3-Back) and low load (0-Back) conditions was counterbalanced. The design, procedure, and instructions were the same as in Experiment 1. As in Experiment 1, the task began with 20 initial titration trials to determine the participants' baseline k . After the initial titration trials, both high load and low load stimuli were presented in a block of 56 ITC trials per condition. All manipulations were within subjects.

Adaptation of choices. The first trial of the first ITC block began with a choice in which the k_{choice} value was equivalent to participants' initially estimated baseline k from titration. The k_{choice} used to construct each subsequent choice changed as a function of previous choice behavior. Specifically, following questions in which the participant chose the sooner reward, the k_{choice} used to construct the next choice was the product of the previous k_{choice} and 1.23. This number was used because it was the largest multiple of k used in Experiment 1 (see Figure 3). Following questions in which the participant chose the later reward, the k_{choice} value used to construct the next choice was the previous k_{choice} divided by 1.23. For example, for a participant with a baseline k value of 0.24, the k_{choice} for the first choice of a condition was 0.24. If the participant chose the sooner option, the next choice adapted to become 0.29. If the later option was selected on the next choice, k_{choice} for the subsequent choice adapted to become 0.24 (see Figure 4). The later choice option values were generated by fitting the hyperbolic discount function with randomly drawn delay values of 2, 4, 6, and 8 weeks, and immediate reward values from a mean of \$12 and a standard deviation of \$5.

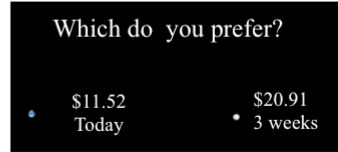
A)

$$k_{\text{choice}} = 0.33$$



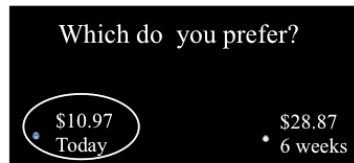
Decrease k_{choice}

$$k_{\text{choice}} = 0.27$$



B)

$$k_{\text{choice}} = 0.27$$



Increase k_{choice}

$$k_{\text{choice}} = 0.33$$

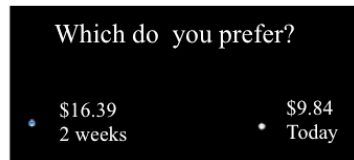


Figure 4. Choice adaptation: A) Following questions in which participants chose the later reward, the k_{choice} value used to construct the next choice was the previous k_{choice} value divided by 1.23. B) Following questions in which participants chose the sooner reward, the k_{choice} value used to construct the next choice was the product of the previous k_{choice} value and 1.23.

At the end of the experiment, one of the ITC choices was randomly selected for remuneration. Participants received the amount of one of the rewards they had selected in the form of an amazon.com gift certificate, which was later emailed to them. For immediate

outcomes, certificates were sent on the same day as the visit to the laboratory. For delayed outcomes, certificates were emailed after the delay specified in the selected choice.

Results

N-Back

Mean N-Back accuracy was 70.8% for the high load condition and 94.7% for the low load condition. Both incorrect and correct trials were included in the analyses presented below.

Effects of WM load

In Experiment 2, the relative change in k_{choice} (now referred to as “change in k_{choice} ”) across trials was the outcome measure, not choice behavior, as in Experiment 1. Change in k_{choice} was measured by subtracting the baseline k from the k_{choice} value for the last trial of a condition. To test for the predicted effect of greater change in k_{choice} under HL than LL (our first prediction), a paired samples t-test was conducted on change in k_{choice} for HL and LL conditions. Contrary to our first prediction, the paired samples t-test revealed no significant difference in change in k_{choice} between the HL ($M = -0.03$, $SE = 0.02$) and LL conditions ($M = -0.04$, $SE = 0.02$; $t(49) = .79$, $p = 0.43$ (2-tailed), Cohen’s $d = 0.06$).

Effects of condition order

In Experiment 2, WM load was manipulated within subjects, with all participants undergoing both the counterbalanced HL and LL conditions. To test for order effect on change in k_{choice} , a two 2 (order) by 2 (change in k_{choice} for HL and LL) ANOVA was conducted with change in k_{choice} as the dependent variable. Although the conditions were counterbalanced, the ANOVA revealed a main effect of order ($F(1, 47) = 6.70$, $p < 0.05$), no main effect of load ($F(1, 47) = .59$, $p = 0.44$), and a non-significant interaction between load and order ($F(1, 47) = .01$, $p = 0.94$).

Effects of WM load: Between subjects comparison

Given the main effect of order, the effect of load for each condition order was analyzed between subjects, based on the condition that participants completed first (i.e., HL for the group that completed the HL condition first, and LL for the group that completed the LL condition first). Participants who received the HL condition first (now referred to as the “HL first group”; $n = 27$) were compared to those who received the LL condition first (now referred to as the “LL first group”; $n = 22$).

Based on our first predictions above, we examined if change in k_{choice} was greater in the HL condition (for the HL first group) than in the LL condition (for the LL first group). Change in k_{choice} for the HL first group ($M = 0.02$, $SE = 0.03$) was significantly greater than change in k_{choice} for the LL first group, $M = -0.09$, $SE = 0.03$, ($t(47) = -2.98$, $p < 0.01$ (2-tailed), Cohen’s $d = -0.87$). This test supports our first prediction that change in k_{choice} would be greater in the HL condition than in the LL condition; however, the effect was found between and not within subjects.

Choice adaptation

In support of our second prediction, the adaptive procedure was predicted to maintain all choices for the sooner and later reward at 50%. Under high load, participants chose the later reward on 48.3% of choices, and, under low load, participants chose the later reward on 48.4% of choices. This indicates that the titration successfully maintained preferences at indifference.

Experiment 2 Discussion

The main effect of order on change in k_{choice} can be interpreted in light of a dual-process theory framework (e.g., Kahneman & Frederick, 2002; Stanovich & West, 2000), as described in Chapter 1. It may be that for the HL first group, a high WM load disrupted the deliberative operations of system 2, allowing for automatic judgments to be made by system 1. Conversely, for the low load first group, system 2 made deliberative evaluations in the first block by suppressing system 1, and this suppression persisted once the high load block began. This interpretation is in line with the current hypothesis that high WM load but not low WM load disrupts cognitive control aspects of ITC, resulting in greater automatic preferences for immediate rewards.

The change in k_{choice} was negative in the low load condition. Although the first choice of each condition was set to participants' baseline k values (from the initial 20 titration trials without WM load), final k_{choice} values fell below the initially estimated baseline k for these participants. In Experiment 1, when choices were presented at the participants' baseline k value, the earlier reward was chosen for less than 50% of choices. These findings from Experiments 1 and 2 suggest that participants' ITC choice behavior during the main part of the experiment was more patient than their initially estimated baseline k from titration. One possible explanation for this increased patience is that participants become more patient or that their strategies shifted due to boredom or fatigue with repeated administration of ITC.

Taking the caveats regarding carryover and increasing patience into account, participants showed significantly less of a negative change in k_{choice} in the HL condition than in the LL condition in the between subjects comparison (Figure 5). While this evidence does not support the predictions that there would be greater impulsivity for the HL condition and no change in

impulsivity for the LL condition, it does indicate that, given the increase in patience, participants under high WM load showed relatively steeper discounting than those under low WM load. This aspect of the results is consistent with Experiment 1.

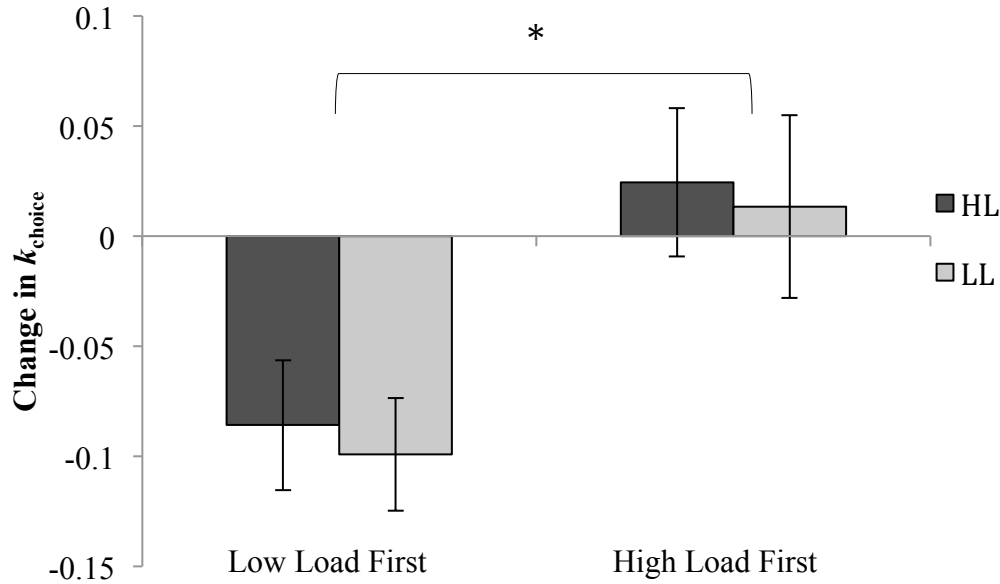


Figure 5. Effect of task order on change in k_{choice} . Error bars indicate one standard error above and below the mean.

Discussion

In this chapter, two experiments were described that were designed to examine the effects of a working memory load on control mechanisms in intertemporal choice. The first two experiments revealed three important findings: (1) a high WM load increased preferences for immediate reward options; (2) behavior from one WM load condition carried over between to the next, from low to high load and vice versa; and (3) participants' strategies shifted toward greater patience with repeated ITC questions. In the next chapter, two experiments are described which

aim to characterize whether the effect of a WM load on control mechanisms in ITC is interference or fatigue and to further address methodological issues in the first experiments.

Chapter 3: Characterizing the Role of Cognitive Control in Intertemporal Choice

Introduction

In Chapter 2, it was hypothesized that the effects of a high working memory load during the N-Back were either due to interference or fatigue of control mechanisms. In this chapter, Experiments 3 and 4 utilized behavioral methods to examine whether a working memory load either fatigues or interferes with control mechanisms during ITC. Here, interference is operationally defined as higher levels of active maintenance during an N-Back task, and fatigue is operationally defined as mental fatigue due to task length. Preferences for immediate rewards were examined in both low and high fatigue and low and high interference conditions. The two main objectives for Experiments 3 and 4 were to: (1) determine if a working memory load causes either interference or fatigue of the cognitive control mechanisms needed for selecting long term rewards; and (2) corroborate work in the previous chapter showing that cognitive load increased preferences for immediate rewards.

The experiments in Chapter 3 also address some of the methodological issues that arose in Chapter 2, including carryover effects between high and low load working memory tasks and increasing patience over multiple ITCs. To account for carryover effects, all manipulations were carried out between subjects. To account for increasing patience over multiple ITCs, participants answered only a single ITC (e.g., Kahneman and Tversky, 1979; Loewenstein, 1988). Given evidence presented in Chapter 2 that greater WM load leads to greater impulsivity, it was predicted that either the high fatigue group, the high interference group, or both groups would select the immediate option more often than the delayed option as compared to the low fatigue and interference groups. At the psychometric level, it was predicted that high fatigue and

interference would tax working memory more than low fatigue and interference conditions and that this effect would be reflected in performance decrements.

Experiment 3

As described in earlier chapters, since dlPFC shows sustained and elevated activity during two and 3-Back WM tasks (Cohen et al., 1997) and is critical for maintaining the goals of a task and inhibiting competing responses (Miller & Cohen, 2001), one possibility is that a higher WM load in the N-Back task either interferes with or fatigues dlPFC function and cognitive control during ITCs, resulting in more impulsive behavior. If impulses for immediate rewards are in competition with mechanisms responsible for more patient decisions in ITC, a working memory load may cause interference such that dlPFC cannot override impulses for immediate rewards while actively maintaining the memoranda. Another possible explanation is that a high working memory load in the N-Back task fatigues (i.e., mental fatigue due to length of the N-back task) limited resources needed in exerting control, resulting in short term impairments in ITC task decisions. Note that fatigue as it is operationalized here is specific to fatigue associated with the length of time spent performing the N-Back task.

Given the between subjects design and that only a single intertemporal choice was provided to participants, these experiments were conducted on Amazon's Mechanical Turk (MTurk; www.Mturk.com) so that a relatively large sample could be recruited. MTurk is an open online labor market in which "workers" (paid task completers) may get paid small wages for micro tasks, and "requestors" (task creators) may post jobs. MTurk workers may browse Human Intelligence Tasks ("HITS") by keyword, reward, title, availability, etc. The MTurk site is one of the largest crowdsourcing subject pools (Mason & Suri, 2011) making the site an excellent tool

for efficient and inexpensive data collection with minimal recruitment effort. More information about MTurk is provided in Appendix A.

Two variants of the N-Back task (either 0-Back or 2-Back) were used to manipulate working memory load in Experiment 3. By manipulating both the number of trials before the ITC and the size of the working memory load, this experiment examined whether fatigue (number N-Back trials) and/or interference (size of N-Back load) leads to greater impulsivity. At the psychometric level, it was predicted that high fatigue and high interference conditions would tax working memory more than low fatigue and interference conditions and that this would be demonstrated by decrements in N-Back performance.

Materials and Methods

Participants. A HIT was posted on Amazon's Mechanical Turk that required workers to complete an externally hosted survey. The HIT was titled "Answer a short decision survey." Participants provided their informed consent to participate in a study on decision-making. The HIT was visible only to workers with an acceptance rate greater than 95% and who were residents in the U.S., based on ownership of a U.S. bank account. Two hundred fifty-nine Amazon Mechanical Turk workers participated in the interference conditions (158 females, *M* age = 29.9 yrs) and 644 Amazon Mechanical Turk workers participated in the fatigue conditions (374 females, *M* age = 27.2). Participants were compensated at the prevailing rates. This study was approved by the Institutional Review Board at Princeton University.

Apparatus and Materials. Experiments were designed using *Qualtrics* software and JavaScript.

Design. Participants were informed that the purpose of the anonymous survey was to examine their preferences for rewards available after different amounts of time. Participants were

instructed that there were no right or wrong answers and that they should do their best to express their true preferences. After providing participants with instructions, two multiple-choice questions were administered to ensure that participants understood the task. Participants were required to correctly answer the multiple-choice questions about the instructions before beginning the experiment; if participants did not answer correctly, they were returned to the beginning of the instructions for up to two attempts. Participants were instructed that they must begin and end the experiment in a single sitting and within the specified time limit in order to receive payment. Participants were also required to complete an instructional manipulation check (IMC), a tool for measuring whether or not participants are reading instructions (Oppenheimer, Meyvis & Davidenko, 2009). The IMC consisted of a question within the survey that resembled the other questions but asked participants to ignore the standard response format and instead confirm that they had read the instructions, (for an example, see Appendix B). The IMC was presented after the main experiment was completed.

All participants received compensation. A single participant from each condition was selected at random to actually receive their expressed preference in the form of an MTurk bonus. The instructions emphasized that if a participant was selected to receive their expressed payment, payment was made the same day as participation if the immediate reward was selected, or after the delay specified in the choice if the delayed option was selected. Performance accuracy was also incentivized, such that participants were told that they would receive a small bonus if they responded accurately on any given randomly drawn trial.

Intertemporal Choice. As previously mentioned, only a single intertemporal choice was provided. The intertemporal choice was “which do you prefer, \$8 now or \$10 in one week?” This question was piloted on Mechanical Turk, with 47% of 100 respondents selecting the immediate

reward (see Figure 6). The appearance of the amounts of \$8 and \$10 was counterbalanced between the left and right side of the screen.

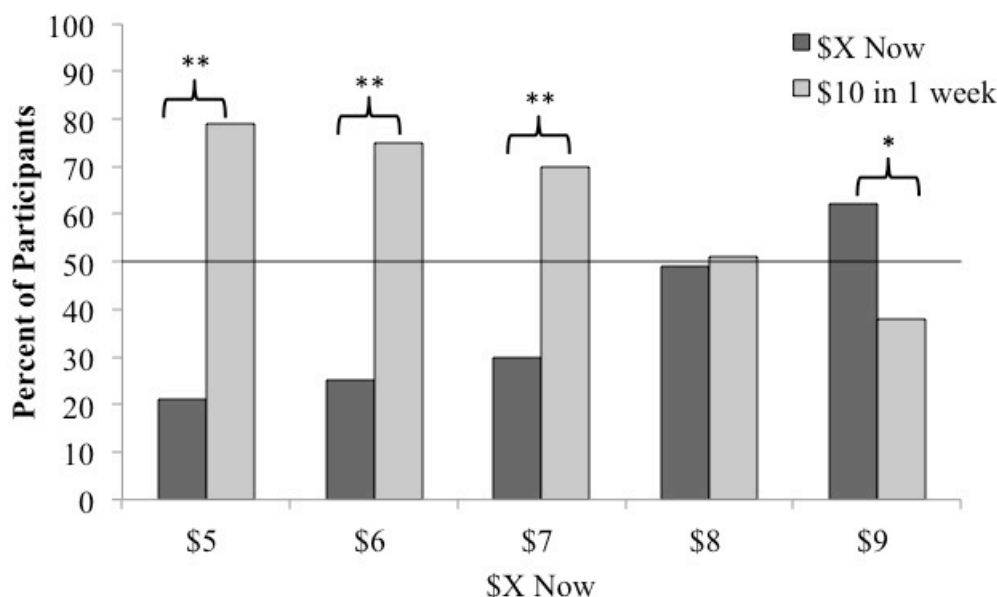


Figure 6. Percent of participants who chose the immediate options for \$5, \$6, \$7, and \$9. The delayed option value was always \$10. Binomial test results revealed that participants were split at approximately 50% for the question of \$8 now versus \$10 in one week. Solid line shows chance level (50%). Binomial test: ** $p < .001$, * $p < .05$. (N = 500).

Interference conditions. As stated above, interference was manipulated by varying the size of the N-Back load. Participants completed one of two variants of the N-Back task, either 2-Back (high interference) or 0-Back (low interference). The N-Back tasks consisted of a continuous stream of letter stimuli presented one at a time. Stimuli were eight phonologically distinct letters (*B, F, K, H, M, Q, R, X*) that were randomly presented in either upper or lower case. Participants in the high interference condition assessed whether the current stimulus matched the stimulus two trials ago. Participants in the low interference condition assessed whether or not the current letter was the letter *M*. Letters were presented in the center of the screen for 1 second, and

participants were instructed to respond as quickly and accurately as possible. Importantly, the ITC preceded either a 0-Back or a 2-Back target so that memory load was not released while the decision was made. Participants had 4 seconds to answer the ITC. Participants were made aware that at some point they would be asked to answer questions about their preferences. Both interference groups completed 20 trials, as shown in Figure 7.

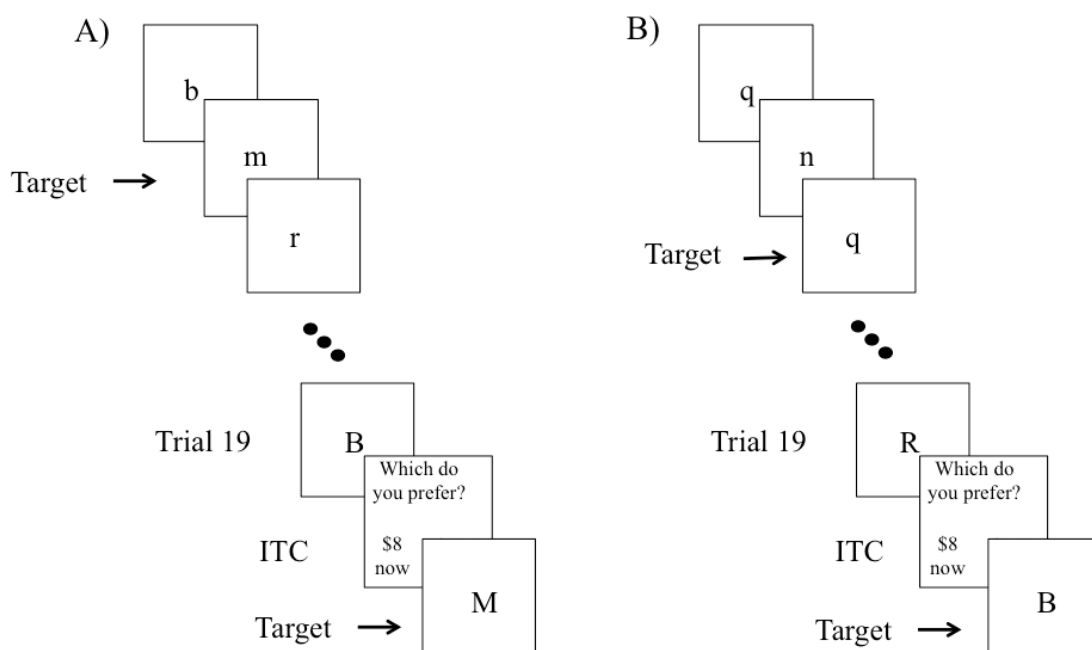


Figure 7. Procedure: low (A) and high (B) interference conditions.

Fatigue conditions. Fatigue was manipulated by varying the number of 2-Back and 0-Back trials appearing before the ITC. As stated in the introduction, the aim was to test whether the length of time spent performing the N-Back task affects discounting performance. Importantly, the ITC appeared after 20 trials for low fatigue and after 70 trials for high fatigue. This is shown in Figures 8 and 9.

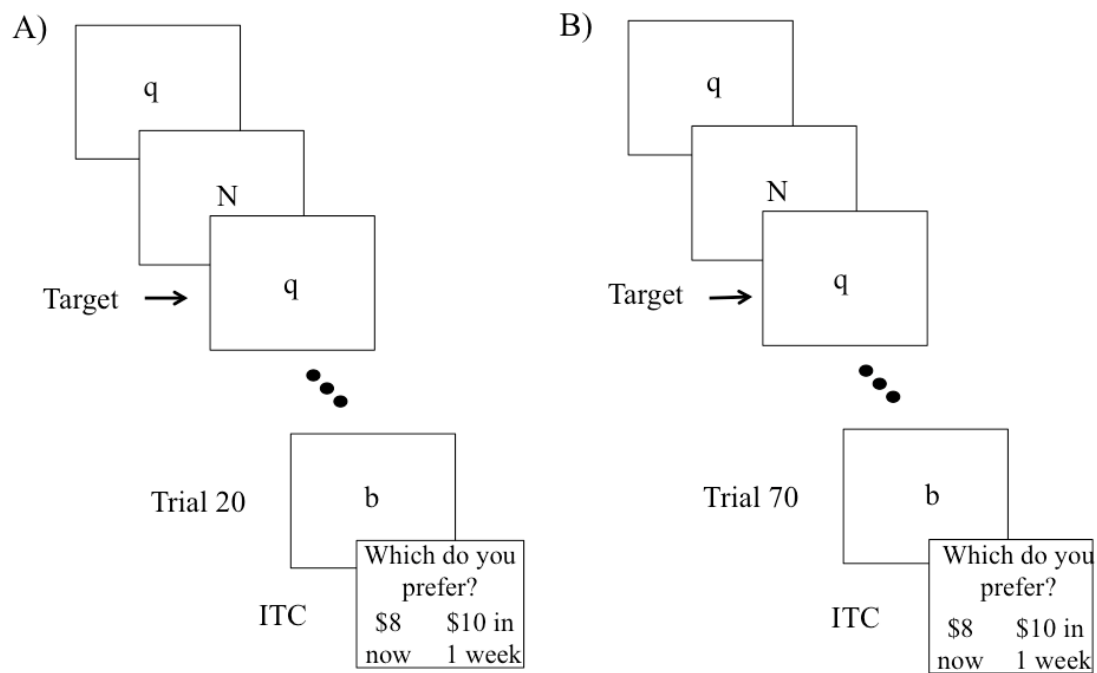


Figure 8. Procedure: 2-Back low (A) and high (B) fatigue conditions.

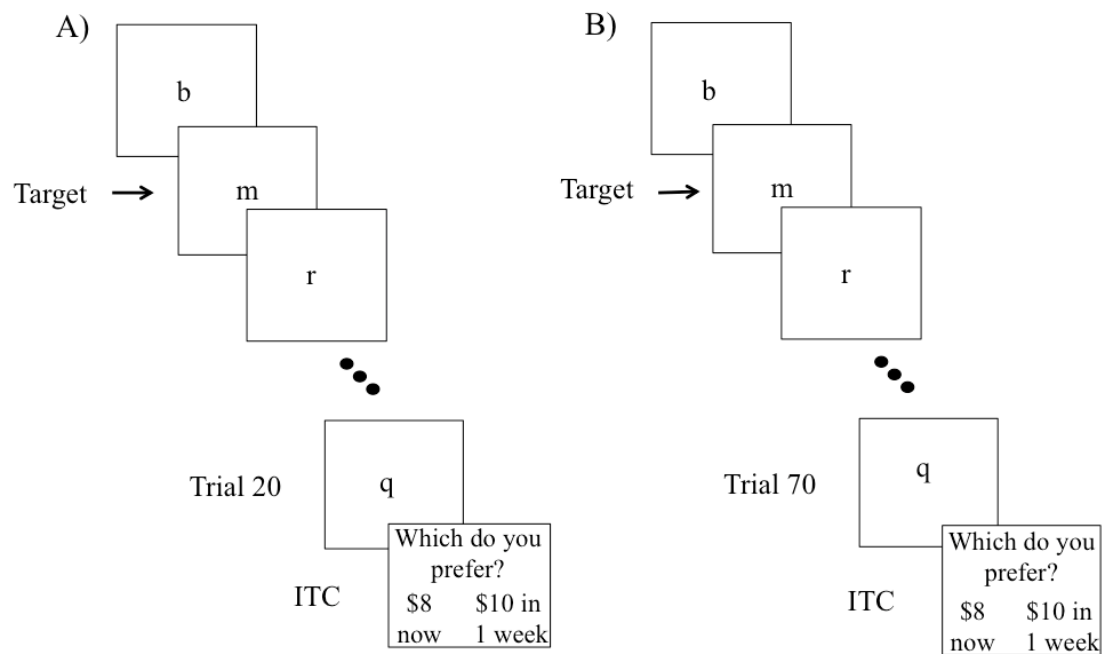


Figure 9. Procedure: 0-Back low (A) and high (B) fatigue conditions.

Results

The three main predictions were that: (1) the high interference, (2) the high fatigue, or (3) both the high interference and high fatigue groups would select the immediate option more often than the delayed option as compared to the low fatigue and interference groups. At the psychometric level, it was predicted that high fatigue and high interference conditions would tax working memory more than low fatigue and interference conditions. It was predicted that this would be reflected in performance decrements in the N-Back task.

Interference

An independent-samples t-test revealed that participants' performance accuracy in the low interference condition ($M = 91\%$, $SE = .01$) was significantly greater than accuracy in the high interference condition ($M = 79\%$, $SE = .01$); $t(257) = 14.17$, $p < .001$.

To test the first prediction that the high interference group would select the immediate option (\$8 now) more often than the delayed option (\$10 in one week), a chi square test was conducted on the high and low interference groups. The chi square test revealed that a significantly greater percentage of participants selected the immediate reward in the high interference group (50%) as compared to the low interference group (38%), $\chi^2(1, N = 259) = 4.10$, $p < .05$ (Figure 10).

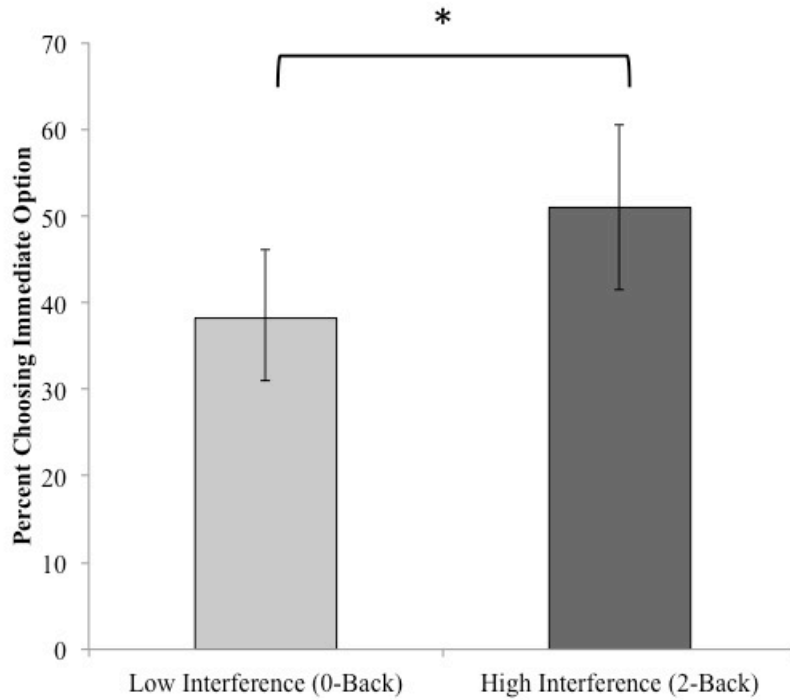


Figure 10. Results: low and high interference conditions. Bars represent 95% confidence intervals of the percentage (Newcombe & Robert, 1998).

Fatigue

An independent-samples t-test revealed that participants' performance accuracy in the 0-Back low fatigue condition ($M = 92\%$, $SE = .01$) was significantly greater than accuracy in the 0-Back high fatigue ($M = 87\%$, $SE = .01$) condition; $t(332) = 2.99$, $p < .01$. Performance accuracy in the 2-Back low fatigue condition ($M = 78\%$, $SE = .01$) did not differ significantly from accuracy in the 2-Back high fatigue condition ($M = 78\%$, $SE = .01$), $t(308) = .17$, $p = .87$.

To test the effects of fatigue across the 0-Back and 2-Back manipulations, a log-linear model was used. In the case of several categorical variables, a log-linear analysis is a more robust analysis than a chi-square test (Howell, 2012). The advantage to using this method is that log-linear models allow for the combination of cross tabulation chi-square testing (i.e. examining

fit between observed and expected frequencies) with features of the ANOVA (i.e., testing of main effects and interactions).¹ A three way contingency test (2 x 2 x 2; fatigue x interference x ITC) using a log-linear model showed ITCs to vary significantly with interference ($LR\chi^2 = 4.87$, $p < .05$), but not with fatigue ($p = .44$), or with the interaction between factors ($p = .78$; Figure 11).

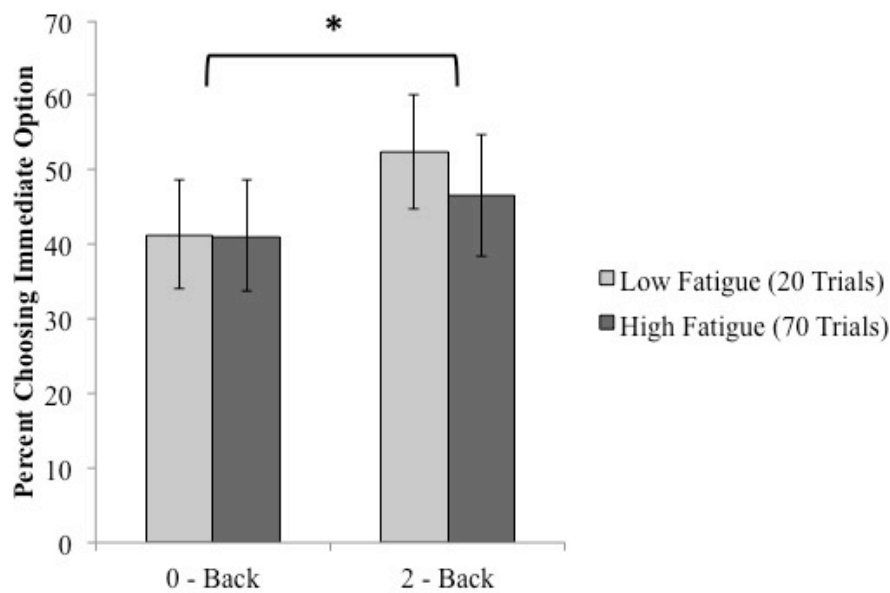


Figure 11. Results: All fatigue conditions. Bars represent 95% confidence intervals of the percentage.

¹ Unlike ANOVA models (which assume linear relationships), a log-linear model assumes multiplicative relationships. The multiplicative model is transformed to a linear model using a logarithm transformation. Note that like the Pearson Chi Square test, there is not independent or dependent factor and the response variable is treated as a factor.

Experiment 3 Discussion

Experiment 3 was designed to test two competing hypotheses: that either interference (i.e., higher level of active maintenance during an N-Back task) or fatigue of control mechanisms (i.e., mental fatigue due to length of the N-back task) results in more impatient intertemporal choices. Results from Experiment 3 suggested that interference of control mechanisms has a greater impact on temporal choice behavior than fatigue of control mechanisms due to task length. Note that the operational definition of fatigue here is specific to the length of the N-Back task; fatigue in general has not been ruled out as a potential factor that may influence ITCs.

This conclusion was supported by the finding that participants were more impulsive under high interference than low interference, as well as by the absence of an effect of high fatigue relative to low fatigue. This conclusion was further supported by the main effect of interference across the 0-Back and 2-Back fatigue conditions. These results also corroborated earlier findings outlined in Chapter 2 by demonstrating that a high working memory load in the high interference condition led to increased preferences for immediate rewards.

These results can be interpreted in light of parallel processing constraints due to the limited capacity of cognitive control. More specifically, the effect of interference rather than fatigue on intertemporal choices supports the hypothesis that maintaining a larger amount of information in WM during the N-Back task while simultaneously performing temporal decisions leads to the disruption of control mechanisms. Given that dlPFC shows sustained and elevated activity during 2 and 3-Back tasks (Cohen et al., 1997), is critical in inhibiting competing responses (Miller & Cohen, 2001), and is implicated in patient temporal choices (Figner et al., 2010; Hare et al., 2009; McClure et al 2004), then it is possible that processing the 2-Back task and temporal decisions in parallel causes interference. The result of this interference is that

dlPFC cannot bias processing in favor of the controlled selection of delayed rewards, leading to more impulsive decision making.

An unanticipated aspect of these results was that participants in the low interference group behaved more patiently than those in the pilot study. It was hypothesized that the effects of a WM load would be most clearly observable when the choice presented was at the indifference point. Due to this, the ITC was engineered so that participants would be indifferent about the sooner and later option. However, results from Experiment 3 indicated that participants were not indifferent to choices offered under low interference, which could have confounded the predicted effects in the high interference condition. Participants in the pilot group and in the interference conditions showed differential sensitivity to the ITC offered. To account for this, a second ITC was piloted in Experiment 4. Experiment 4 also leveraged the same interference and fatigue manipulations as Experiment 3.

Experiment 4

Experiment 4 had two main objectives. The first was to further examine the effects of interference and fatigue on ITC control mechanisms. As noted in Experiment 3, the operational definition of fatigue here is specific to the length of the N-Back task. The second objective was to replicate Experiment 3 with an ITC that elicited equal preferences for the sooner and later rewards under low interference. It was predicted that that participants would choose the sooner reward more often under high interference than low interference due to greater disruption of control mechanisms needed for selecting long term rewards.

Materials and Methods

The details of the HIT posted on MTurk followed those outlined above for Experiment 3. The methods also followed those outlined in Experiment 3.

Participants. Two hundred seventy-two Amazon Mechanical Turk workers participated in the interference conditions (155 females, M age = 30) and 603 Amazon Mechanical Turk workers participated in the fatigue conditions (380, M age = 27.6). Participants were compensated at the prevailing rates. The Institutional Review Board at Princeton University approved this study. All subjects provided informed consent prior to participation.

Design.

The design followed that of Experiment 3, with the caveat that the ITC for all interference and control conditions was, “which do you prefer, \$9 now or \$10 in one week?” The appearance of the amounts of \$9 and \$10 was counterbalanced between the left and right side of the screen. This choice was piloted with another sample of pilot subjects and proved to elicit equal preferences for the immediate and delayed reward (Binomial test $p < .05$, $N = 100$).

Results

Interference

An independent-samples t-test revealed that participants’ performance accuracy in the low interference ($M = 89\%$, $SE = .01$) condition was significantly greater than accuracy in the high interference ($M = 79\%$, $SE = .01$) condition; $t(270) = 12.42$, $p < .001$.

To test the effects of interference, a log-linear model was used as in Experiment 3. A three way contingency test ($2 \times 2 \times 2$; interference x choice x ITC) using a log-linear model

showed ITCs to vary significantly with interference ($LR\chi^2 = 10.40, p < .05$), as well as with choice offered in Experiments 3 and 4 (either \$8 or \$9 as the immediate option; $LR\chi^2 = 6.45, p < .05$), but not with the interaction between factors ($p = .77$; Figure 12).

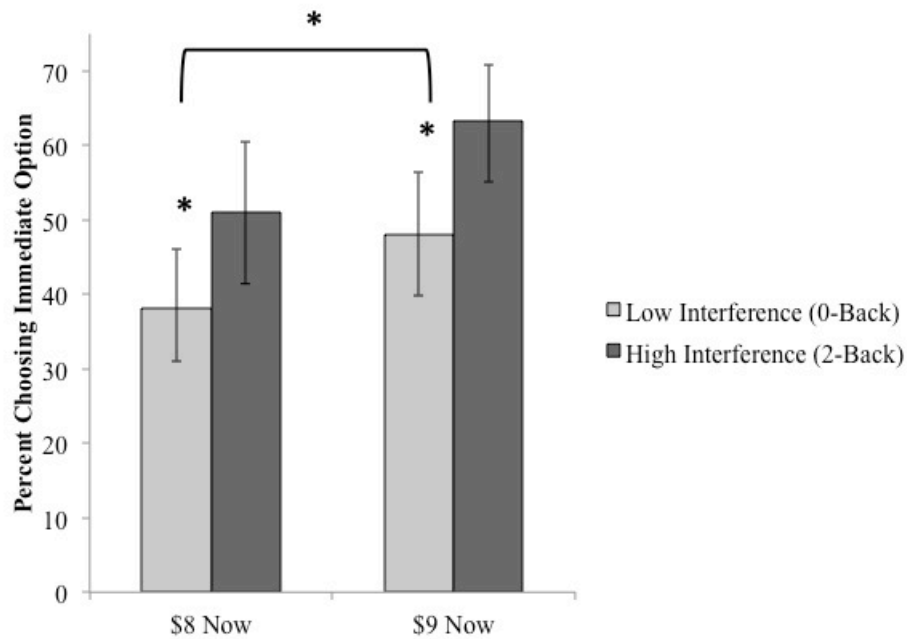


Figure 12. Results: All interference conditions from Experiments 3 and 4. Bars represent 95% confidence intervals of the percentage.

Fatigue

An independent-samples t-test revealed that participants' average performance accuracy in the 0-Back low fatigue ($M = 93\%$, $SE = .01$) was not significantly greater than accuracy in the 0-Back high fatigue ($M = 92\%$, $SE = .01$) condition, $t(312) = .21, p = .85$. Participants' average

performance accuracy in the 2-Back low fatigue ($M = 76\%$, $SE = .01$) did not significantly differ than accuracy in the 2-Back high fatigue ($M = 76\%$, $SE = .01$) condition, $t(287) = .17$, $p = .87$.

To test the effects of fatigue across the 0-Back and 2-Back manipulations, a three way contingency test ($2 \times 2 \times 2$; fatigue $\times$ interference $\times$ ITC) using a log-linear model showed ITCs did not vary with fatigue ($p = .12$), with interference ($p = .72$) or with the interaction between factors ($p = .91$; Figure 13).

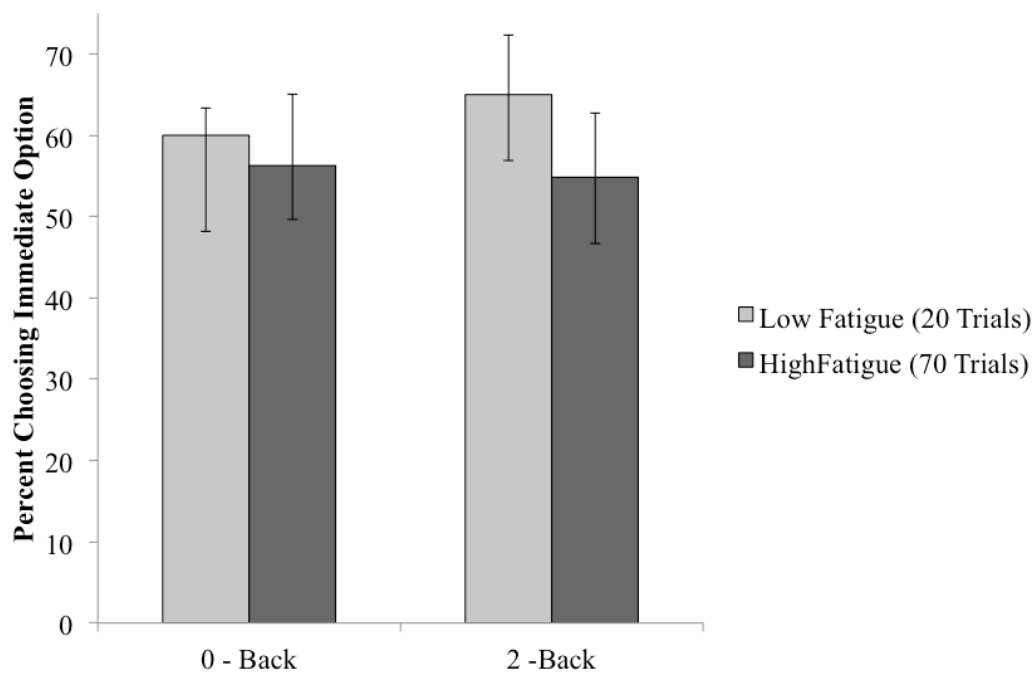


Figure 13. Results: All fatigue conditions. Bars represent 95% confidence intervals of the percentage.

Experiment 4 Discussion

In Experiment 4, it was predicted that participants would choose the sooner reward more often under high interference than low interference due to greater disruption of control mechanisms needed for selecting long term rewards. Taken together, these findings replicated those of Experiment 3 and supported the conclusion that interference rather than fatigue leads to greater preferences for immediate rewards. This aspect of the results was supported by more participants choosing the sooner option under high interference.

Discussion

The experiments in this chapter were designed to assess whether fatigue or interference of control mechanisms influences ITC behavior. The operational definition of fatigue here is specific to the length of the N-Back task. Though fatigue in general has not been ruled out as a potential factor that may influence ITCs, these experiments support the conclusion that interference of control processes influences ITC behavior such that participants are more impatient under high interference conditions. In Chapter 4, interference manipulations will be used to examine the role of control processes in framing paradigms that typically elicit more patient ITCs.

Chapter 4: The Role of Control in Framing Effects

Introduction

In Chapter 3, Experiments 3 and 4 showed that interference (i.e., higher levels of active maintenance during an N-Back task) rather than fatigue (i.e., mental fatigue due to task length) disrupts control mechanisms hypothesized to be needed for the selection of delayed rewards in ITC. The experiments presented in this chapter were designed to characterize the role of control mechanisms in framing manipulations that lead to greater patience during ITCs. It is predicted that if cognitive control underlies framing effects that elicit greater patience, an interaction should be observed between the interference and framing effects.

Experiment 5

The way in which gambles are framed can influence preferences. Lowenstein and Thaler demonstrated that asking participants how much they would need to be compensated to delay a good from $t + s$ produced significantly greater discounting than when accelerating its receipt from $t + s$ to t . This phenomenon is referred to as “acceleration effects,” also referred to in the literature as “asymmetric discounting” or “speed up/ slow down asymmetry” (Loewenstein, 1988). Acceleration effects have been explained in terms of loss aversion, such that delayed consumption of a reward is encoded as a loss and accelerated consumption is encoded as a gain (Kahneman & Tversky, 1979).

In an effort to provide a psychological account for asymmetric discounting, Weber et al. (2007) also demonstrated that people discount less steeply when intertemporal choices are framed in terms of accelerated consumption as compared to delayed consumption (see also Loewenstein 1987; 1988). Weber et al. provided a process-level account of asymmetric

discounting and proposed that asymmetric discounting can be supported and explained by query theory. According to query theory, delaying or accelerating consumption of a reward influences the order in which one queries their memory to support either delayed or accelerated consumption. The order of queries in turn affects the number of patient and impatient thoughts, which in turn affects the decision outcome.

The goal of Experiment 5 was to examine whether greater exertion of cognitive control underlies acceleration effects. If greater patience in acceleration framing is the result of greater exertion of cognitive control, then interference of control mechanisms with a high WM load should attenuate acceleration effects. To examine this possibility, participants in Experiment 5 responded to either delayed or accelerated intertemporal choices, while under either a high or low WM load. Based on the hypothesis that cognitive control is necessary to shift decisions toward greater patience, two predictions were made: 1) a main effect of framing such that participants in the acceleration conditions show greater patience overall than participants in the delay conditions (i.e., a replication of the acceleration effect); and 2) an interaction between interference and framing factors such that the high interference manipulation will attenuate acceleration effects (i.e., support for the hypothesis that greater control underlies acceleration effects).

Materials and Methods

Participants. As in Chapter 3, a Human Intelligence Task (HIT) was posted that required workers to complete an externally hosted survey. Three hundred eighty-nine Amazon Mechanical Turk workers participated in (241 female, M age = 29.5). Participants were

compensated at the prevailing rates. All subjects provided informed consent prior to participation.

Design. A 2 x 2 between subjects factorial design was used to examine the effects of framing (delay or acceleration) and interference (high or low) on discount rates. Participants were assigned to one of four conditions: low interference acceleration, high interference acceleration, low interference delay, or high interference delay.

Participants were informed that the purpose of the anonymous survey was to examine their preferences for rewards available after different amounts of time. Participants were instructed that there were no right or wrong answers and that they should do their best to express their true preferences. Practice questions were given to familiarize participants with the task. Participants were required to correctly answer two multiple-choice questions about the instructions before beginning the experiment. If the multiple-choice questions were not answered correctly, they were given two more attempts to correctly respond. Participants were instructed that they must begin and end the experiment in a single sitting and within the specified time limit in order to receive payment. Participants were also required to complete an instructional manipulation check (IMC), as described in Chapter 3.

Intertemporal choice conditions

Similar to Weber et al. (2007), participants assigned to the delay conditions were told that they were selected to possibly receive a \$10 Amazon.com gift certificate that day, but they could opt to receive a gift certificate of larger value in 3 weeks. One participant from each condition was selected to actually receive their expressed preference. As in previous studies, pilot work was conducted to determine that participants equally prefer receiving \$10 now versus \$15 in 3

weeks (Binomial test $p < .05$, $N=100$). Participants assigned to the delay conditions were then given a series of choices between a \$10 bonus that day and a larger bonus 3 weeks later; the value of the delayed certificate increased from \$10 to \$20 in \$1 increments (Figure 14). The format of the intertemporal choice followed the Becker-DeGroot Marshak procedure ([BDM]; Becker, DeGroot & Marshak, 1964), which asks a series of multipart questions. In this procedure, within a single question, one option is held constant (either money or time) and the other is varied, in order to measure indifference points.

You have been selected to possibly receive a \$10 bonus today, but you can opt instead to receive a bonus of larger value in 3 weeks.

Which one do you prefer? Pick one option from each pair below.

\$10 Today	☐	☐	Or \$10 in 3 weeks
\$10 Today	☐	☐	Or \$11 in 3 weeks
\$10 Today	☐	☐	Or \$12 in 3 weeks
\$10 Today	☐	☐	Or \$13 in 3 weeks
\$10 Today	☐	☐	Or \$14 in 3 weeks
\$10 Today	☐	☐	Or \$15 in 3 weeks
\$10 Today	☐	☐	Or \$16 in 3 weeks
\$10 Today	☐	☐	Or \$17 in 3 weeks
\$10 Today	☐	☐	Or \$18 in 3 weeks
\$10 Today	☐	☐	Or \$19 in 3 weeks
\$10 Today	☐	☐	Or \$20 in 3 weeks

Figure 14. Procedure: ITC format for delay conditions.

Participants assigned to the acceleration conditions were told that they had been selected to possibly receive a \$15 bonus in 3 weeks but could opt instead to receive a bonus of lesser value that day. Participants were then given a series of choices between a \$15 bonus in 3 weeks and a bonus that day; the value of the immediate bonus decreased from \$15 to \$5 in \$1 decrements. This is shown in Figure 15. To ensure that participants understood the payout structure and the bonuses, participants were required to answer two multiple-choice questions regarding payment correctly before continuing with the study.

You have been selected to possibly receive a \$15 bonus in 3 weeks, but you can opt instead to receive a bonus of lesser value today.

Which one do you prefer? Pick one option from each pair below.

\$15 in 3 weeks	☐ ☐	Or \$15 Today
\$15 in 3 weeks	☐ ☐	Or \$14 Today
\$15 in 3 weeks	☐ ☐	Or \$13 Today
\$15 in 3 weeks	☐ ☐	Or \$12 Today
\$15 in 3 weeks	☐ ☐	Or \$11 Today
\$15 in 3 weeks	☐ ☐	Or \$10 Today
\$15 in 3 weeks	☐ ☐	Or \$9 Today
\$15 in 3 weeks	☐ ☐	Or \$8 Today
\$15 in 3 weeks	☐ ☐	Or \$7 Today
\$15 in 3 weeks	☐ ☐	Or \$6 Today
\$15 in 3 weeks	☐ ☐	Or \$5 Today

Figure 15. Procedure: ITC format for acceleration conditions.

Working memory conditions

WM load was manipulated using the interference manipulations from Experiments 3 and

4. Specifically, WM load was manipulated by varying the size of the N-Back load. Participants completed one of two variants of the N-Back task, either 2-Back (high interference) or 0-Back (low interference). The N-Back tasks consisted of a continuous stream of letter stimuli presented one at a time. Stimuli were eight phonologically distinct letters (*B, F, K, H, M, Q, R, X*) that were randomly presented in either upper or lower case. Participants in the high interference condition assessed whether the current stimulus matched the stimulus two trials ago. Participants in the low interference condition assessed whether or not the current letter was the letter *M*. Letters were presented in the center of the screen for 1 second, and participants were instructed to respond as quickly and accurately as possible. Importantly, the ITC preceded a 2-Back target so that memory load was not released while the decision was made. Participants had 4 seconds to answer the ITC. Both low and high interference condition consisted of 20 trials. The low and high interference conditions are shown in Figures 16 and 17, respectively.

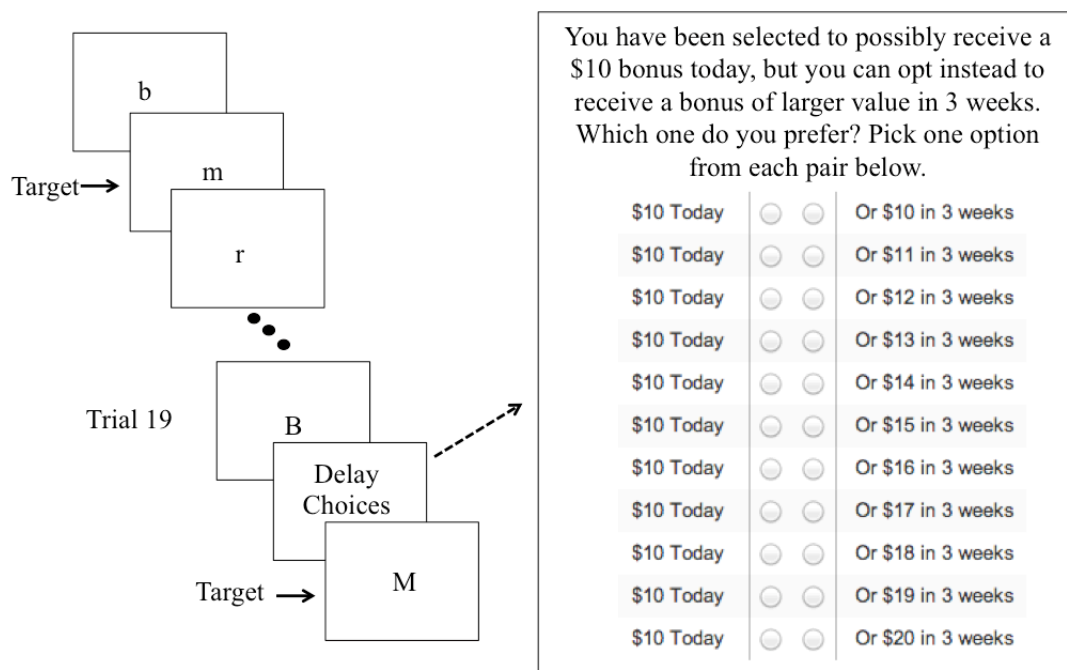


Figure 16. Procedure: Low interference delay condition. In the high interference delay condition, participants completed a 2-Back task.

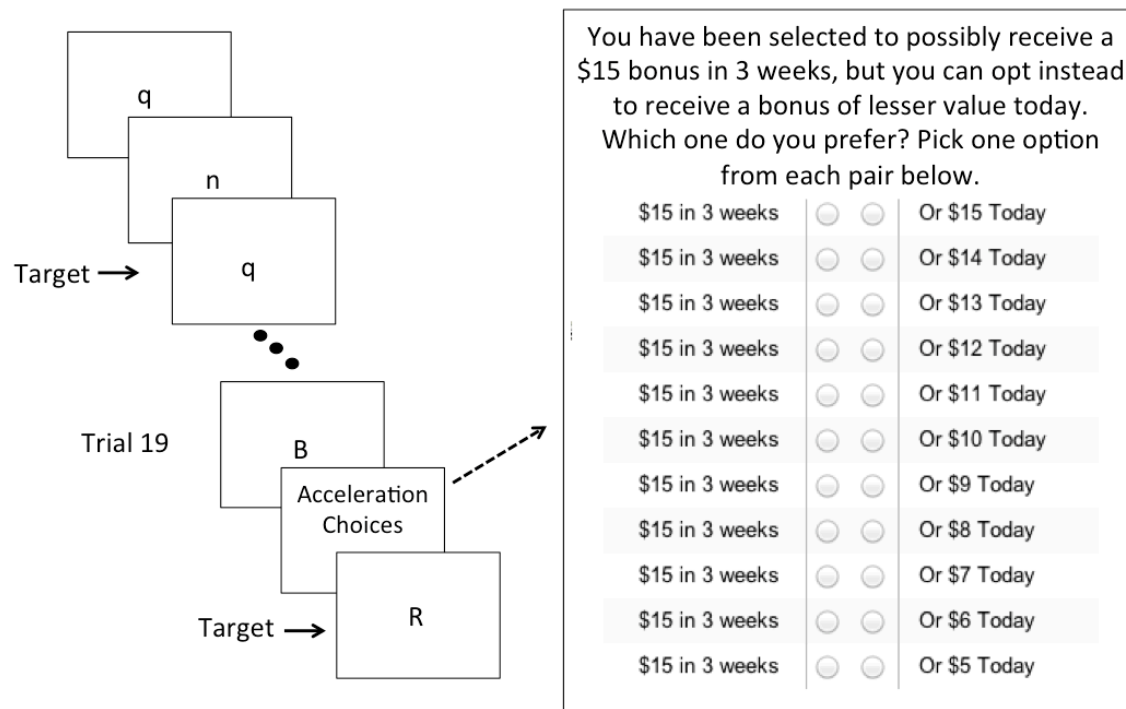


Figure 17. Procedure: High interference acceleration condition. In the low interference acceleration condition, participants completed a 0-Back task.

Results

N-Back

Mean N-Back accuracy was 92% for the low interference group and 76% for the high interference group.

Discount Rates

Based on the choices made during the BDM procedure, discount rates were quantified using the hyperbolic discounting function $V = A/(1+kD)$, where V is the amount received that day, A is the amount to be received in 3 months, D is the delay, and k is the individual discount rate. Larger values of k indicate greater discounting.

Two predictions were made in this experiment: 1) a main effect of framing such that participants in the acceleration conditions would show greater patience overall than participants in the delay conditions (i.e., a replication of the acceleration effect); and 2) there would be an interaction between interference and framing factors such that the high interference manipulation would attenuate acceleration effects (i.e., support for the hypothesis that greater control underlies acceleration effects).

To test these predictions, a 2 (framing) by 2 (interference) ANOVA was conducted with discount rate (k) as the dependent variable. In line with the first prediction, the ANOVA revealed a main effect of framing, $F(1, 389) = 5.71, p < .05$, such that mean discount rates were significantly higher in the delay conditions ($M = .17, SE = .01$) as compared to the acceleration conditions ($M = .14, SE = .01$; Figure 18). The main effect of interference was also significant, $F(1, 389) = 10.26, p < .05$, such that the mean discount rates in the high interference conditions ($M = .18, SE = .01$) were significantly greater than in the low interference conditions ($M = .14, SE = .01$). Contrary to our second prediction, the interaction between the interference and framing factors was not significant, $F(1, 389) = .63, p = .43$.

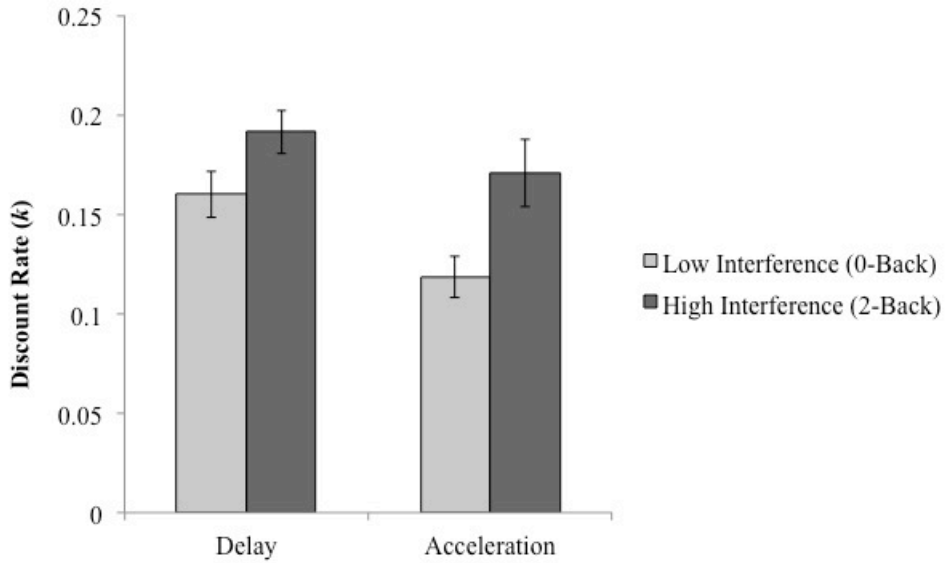


Figure 18. Results from the 2 (framing) by 2 (interference) ANOVA with discount rate (k) as the dependent variable. Error bars indicate one standard error above and below the mean.

Experiment 5 Discussion

The goal of this experiment was to examine the role of cognitive control in acceleration effects. It was hypothesized that if greater exertion of control underlies acceleration effects, a high working memory load, but not a low working memory load should attenuate these effects. Based on the hypothesis that cognitive control is necessary to shift decisions toward greater patience, two predictions were made: 1) a main effect of framing such that participants in the acceleration conditions would show greater patience overall than participants in the delay conditions (i.e., a replication of the acceleration effect); and 2) there would be an interaction between interference and framing factors such that the high interference manipulation would attenuate acceleration effects (i.e., support for the hypothesis that greater control underlies acceleration effects). In support of our first prediction, we successfully replicated the acceleration effect, as demonstrated by the main effect of framing. A main effect of interference

was also observed, supporting earlier claims in this thesis that higher levels of working memory load in the N-Back task interfere with control mechanisms leading to greater discounting.

According to the query theory account of acceleration effects, the order in which one queries memory influences decision-making processes, and because patient thoughts are queried first when choices are accelerated, the resultant behavior is more patient. The goal of this experiment was to further examine the mechanism underlying query theory, and it was predicted that if greater recruitment of control mechanisms underlies acceleration effects, an interaction would be observed between the framing and interference factors. Since the interaction was not significant, this hypothesis was not supported.

While we did not observe an interaction between the acceleration and interference effects, it is possible that heightened recruitment of control mechanisms underlies query theory but that the present N-Back manipulation was not sensitive enough to disrupt these processes. Regardless, our data support the interference effect found in previous experiments in this thesis. Future behavioral research could examine the role of control and attention in acceleration effects by instructing participants to explicitly attend to the second component of a choice framed as either delayed or accelerated. If control and attention underlies these effects, then such a manipulation may attenuate acceleration effects. Future imaging research could also contrast delay and acceleration conditions and examine if there is greater activity in brain regions associated with cognitive control during the acceleration condition.

Experiment 6

In a recent fMRI study, Peters and Büchel (2010) showed that adult participants were more patient when intertemporal choices were tagged with participant-specific future episodic

events. For example, instead of a standard delay, the larger later reward was tagged with “vacation Paris” or “birthday John”. In their fMRI results, when the episodic condition (the condition for which choices were tagged with personal episodic events) was contrasted with the standard control condition, greater activity in some regions associated with the delta network was observed including dlPFC, lateral parietal cortex, and anterior cingulate cortex (ACC). Though Peters and Büchel acknowledged that these findings were in line with the dual process (McClure et al., 2004) and self-control (Figner et al., 2010) models of ITC, they eschewed this possibility.

Peters and Büchel (2010) hypothesized that thinking about the future affects decision making through the involvement of the hippocampus. This hypothesis is based on evidence that the hippocampus has a role in vivid event representations in the past, present, and future, as well as self-projection into the future (Bar, 2009; Schacter & Addis, 2009; Schacter et al., 2007). Peters and Büchel hypothesized that the hippocampus contributes to decision making through its role in self-projection into the future (see also Johnson & Redish, 2007; Johnson et al., 2007). Peters and Büchel support this hypothesis by showing that greater neural coupling between the hippocampus and ACC predicted less impulsive choices.

In the research performed here, it is hypothesized that decreased discounting in the tag effect may be the result of greater recruitment of control mechanisms and that, due to interference of control mechanisms, a high WM load may attenuate the “tag effect”. To test this hypothesis, participants in this experiment completed future episodic conditions under both a high and low WM load. Based on previous findings that the degree of discounting is inversely related to the degree of future oriented thinking and recruitment of control regions, it was predicted that: 1) there would be a replication of the tag effect such that participants in the

episodic condition would choose the immediate option less often than participants in the control conditions; and 2) a high (but not a low) WM load would attenuate the tag effect.

Materials and Methods

Participants. Sixty (26 female, *M* age = 19.7) students at Princeton University participated either for payment or for partial course credit. This study was approved by the Institutional Review Board at Princeton University. All subjects provided written, informed consent prior to participation.

Design. A 2 x 2 between subjects factorial design was used to examine the effects of episodic tag (either control or episodic) and interference (either high or low) on the number of choices for immediate rewards. Participants were assigned to one of four conditions: low interference control, high interference control, low interference episodic, or high interference episodic.

Monetary Choice Questionnaire

Experiment 6 consisted of two parts. In part 1, participants were first emailed a link to complete a brief Monetary Choice Questionnaire, as shown in Appendix C (MCQ; Kirby, Petry, & Bickel, 1999). The MCQ is a self-report questionnaire in which participants are asked to choose repeatedly between two hypothetical rewards: a smaller reward sooner or a larger reward later, such as, “Would you prefer \$27 now or \$50 in three weeks?” The scale is comprised of 27 choices of varying sizes and delays, with each choice contributing to an estimate of a respondent’s discount rate. This scale was used because it has been successfully implemented by other intertemporal choice researchers in the measurement of discount rates (e.g., Charlton et al., 2013; Luo, Ainslie & Monterosso, 2012; Luo, Ainslie, Giragosian, & Monterosso, 2009).

Intertemporal choices were generated for each participant using their specific discount rate. Discount rates were determined using the simple hyperbolic function, which was described previously.

Personal events survey

Similar to Peters and Büchel, participants assigned to the episodic conditions first completed a personal events survey in part 1. In the survey, participants answered questions that prompted them to list future events they had planned with delays between a few days to seven months (e.g., vacations, weddings, parties, courses and so forth). An example is shown in Appendix D. All events were rated on seven-point scales for arousal, valence, and personal relevance. For each participant, a single future event that roughly matched with the mean ratings of all the other events for that participant on arousal, valence, and personal relevance was selected. Only neutral or positive events were used for the episodic tags. The event was associated with a cue or an episodic tag, such as, “Theatre Performance,” to be used during later testing.

Working memory conditions

The WM manipulation was included in part 2 of the experiment. WM load was manipulated using the interference manipulations from Experiments 3, 4 and 5 by varying the

size of the N-Back load (either 0-Back or 2-Back). This is shown in Figure 19.

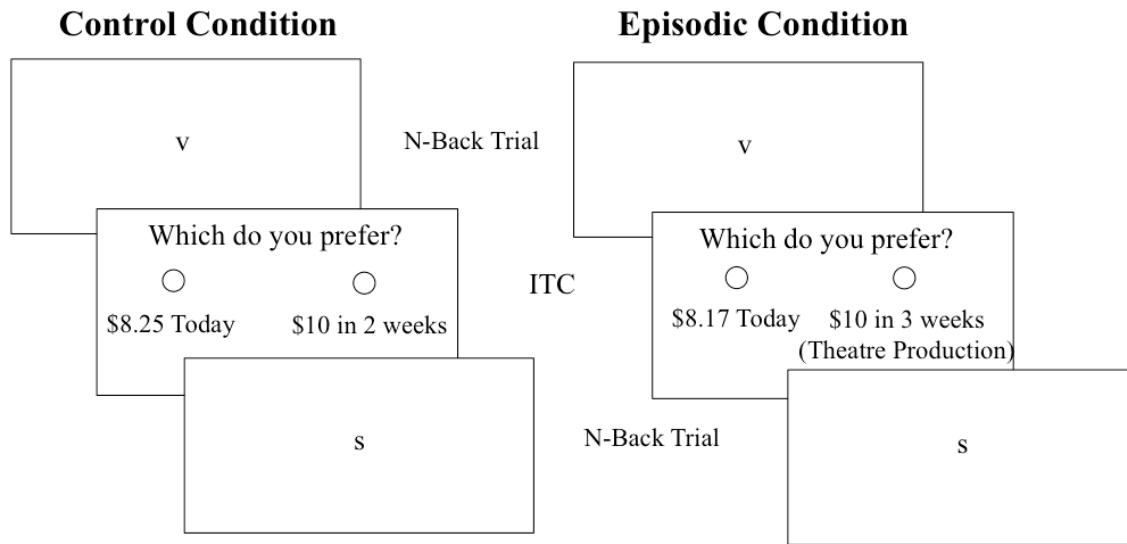


Figure 19. Procedure: Control and Episodic conditions.

Intertemporal choice task

In part 2 of the experiment, participants were emailed a link to complete the low interference control, high interference control, low interference episodic, or high interference episodic task. As in previous experiments, all conditions included a single ITC trial. In the episodic condition, an episodic tag indicating what event participants had planned at that delay accompanied the delay. In the control condition, only the delay was displayed (Figure 19). Delays in the control conditions matched those in the episodic conditions. Participants were told that one person would be randomly drawn from the pool of participants to receive their expressed preference. As described above, intertemporal choices were generated for each participant using their specific discount rate. The future amount was always \$10 and the immediate amount was determined based on the participant specific discount rate.

Similar to Peters and Büchel, for participants in the episodic condition, episodic tags were presented in addition to the delay, to remind participants what they had planned at the respective delay.

Results

N-Back

Mean N-Back accuracy was 95% for the low interference groups and 89% for the high interference groups.

Episodic Effects

This experiment tested the hypothesis that greater recruitment of control mechanisms underlies the tag effect. To test this hypothesis, participants in this experiment completed future episodic conditions under both a high and low WM load. It was predicted that: 1) there would be a replication of the tag effect such that participants in the episodic condition would choose the immediate option less often than participants in the control conditions; and 2) a high (but not a low) WM load would attenuate the tag effect.

A Fisher's exact test was utilized because of low observed frequencies (Howell, 2012). The exact test revealed a replication of the tag effect such that the percentage of participants selecting the immediate reward was significantly lower in the episodic conditions (75%) than in the control conditions (96%; $p < .05$; See Figure 20). Thus, the first prediction was supported.

The second prediction was not supported, as there was not a significant attenuation in the percentage of participants choosing immediate rewards in the high interference episodic condition, as supported by the non-significant difference between high and low interference episodic conditions ($p = .41$).

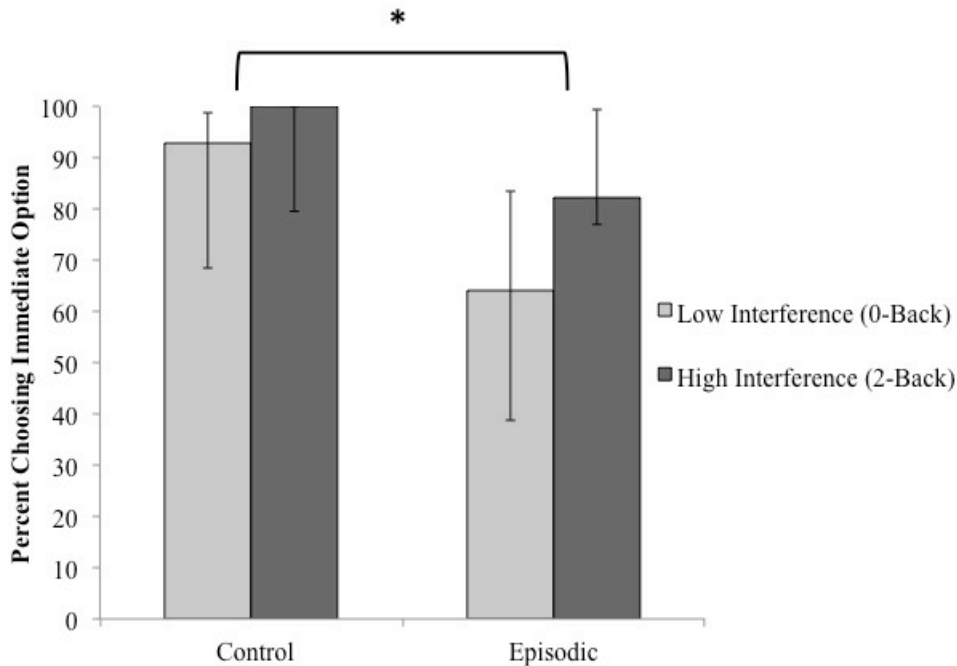


Figure 20. Percentages of participants choosing the immediate reward were significantly different between the control and episodic condition ($p < .05$) indicating a replication of the tag effect. Bars represent 95% confidence intervals of the percentage.

Experiment 6 Discussion

This experiment employed a novel paradigm that leveraged a previous finding that future episodic thinking reduces discount rates, or the “tag effect” (Peters & Büchel, 2010). Participants in this experiment made judgments that were either tagged with future episodic events or with a date in the future (the control condition). Based on the hypothesis that greater recruitment of control mechanisms underlies the tag effect, it was predicted that: 1) there would be a replication of the tag effect such that participants in the episodic condition would choose the immediate option less often than participants in the control conditions; and 2) a high (but not a low) WM load would attenuate the tag effect.

These results support previous findings that future episodic manipulations decrease discounting, as evidenced by the replication of the tag effect (Benoit, Gilbert & Burgess, 2011; Peters & Büchel, 2010). However, they do not support the hypothesis that a high working memory load would attenuate the tag effect; furthermore, the results suggest that it is not control processes per se that underlie the tag effect. As argued by Peters and Büchel (2010), it is likely that the hippocampus contributes to decision-making through its function in self-projection into the future, allowing the decision maker to evaluate future rewards through mental simulation (see also Johnson & Redish, 2007; Johnson et al., 2007).

Discussion

The experiments in this chapter were designed to address whether greater recruitment of control processes underlies framing effects that elicit greater patience. In Experiment 5, we replicated the acceleration effect as well as the interference effect found in earlier experiments in this thesis. However, we did not find evidence to support the hypothesis that greater recruitment of control mechanisms underlies the acceleration effect. The results from Experiment 6 suggest that control-based strategies do not underlie the tag effect; rather, participants may rely on more hippocampal-based prospective strategies. In the next chapter, the overall conclusions and limitations of thesis are discussed as well as directions for future research.

Chapter 5: Thesis Summary and Future Directions

Introduction

This purpose of this thesis has been to examine the role of cognitive control mechanisms in intertemporal choice (ITC). It was hypothesized that the role of cognitive control in ITC may be to bias processing in favor of long-term rewards. Given that dlPFC is sensitive to higher working memory loads in the N-Back task and is thought to have a role in active maintenance of task-relevant information in working memory, the effect of a cognitive load during ITC may be that dlPFC cannot mediate the bias signals needed for the controlled selection of delayed rewards while actively maintaining representations in working memory. Thus, it was hypothesized that interfering with or fatiguing control mechanisms with a high working memory load in the N-Back task should lead to more impulsive choices. In addition to providing support for this hypothesis, the research outlined here also examined whether the nature of the disruption with the N-Back task could be characterized as fatigue or as interference of control mechanisms. The final experiments were designed to test the theory that greater exertion of control mechanisms underlies subtler manipulations that elicit decreased discounting.

This work was successful at demonstrating that a higher working memory load in the N-Back task leads to more impulsive responding via interference with rather than fatigue of control mechanisms needed for patient decisions. This work also resolved prior concerns in the literature and highlighted and addressed several methodological issues. This chapter will outline a general synopsis of the major conclusions from the experiments, address limitations of the work, and suggest avenues for future research.

Conclusions

On the whole, the experiments presented in this thesis provide evidence for the role of control in intertemporal choice; that is, the role that control plays in selecting long-term rewards and how it can be interrupted with an N-back task, leading to more relative impatience. Specifically, this thesis focused on three main questions: 1) does the disruption of control mechanisms lead to more impulsive ITCs?; 2) is this disruption fatigue or interference?; and 3) does greater exertion of control underlie framing effects that elicit decreased discounting? The first two experiments in Chapter 2 demonstrated that disrupting control mechanisms with a cognitive load leads to more impulsive choices, addressed previous concerns in the literature, and highlighted some important methodological issues. The experiments in Chapter 3 addressed those methodological issues raised in Chapter 2 and provided evidence to support the conclusion that a higher working memory load in the N-Back task interferes with, rather than fatigues, control mechanisms in ITC. In Chapter 4, Experiments 5 and 6 were designed to determine the role of control mechanisms in paradigms that elicit reduced discounting. Results from Experiments 5 and 6 suggest that the interference effect does not interact with these subtler manipulations that elicit decreased discounting. Each of these findings is addressed below.

Does interference via the N-Back task lead to more impulsive behavior?

There are several studies presented in Chapter 1 that highlight the importance of cognitive control mechanisms and supporting brain regions in temporal decision making (e.g., Figner et al., 2010; Hare et al., 2009; McClure et al., 2004). The aim of Chapter 2 was to provide evidence that cognitive control is necessary for making patient decisions and that the disruption of these processes leads to relative impulsivity. In an earlier investigation, Hinson et al. (2003)

similarly attempted to use a WM load to disrupt discounting behavior. However, their results were met with concern because impulsive responding was confounded with erratic responding. To address these issues in the experiments performed for this thesis, paradigms were developed to measure baseline-discounting behavior and dynamically adapt to changes in preferences over the course of the experiment. By way of addressing these methodological issues, these experiments were able to demonstrate that a high WM load leads to more impulsive choices.

Two important methodological considerations emerged in Chapter 2. The first was that, with repeated intertemporal choices, participants became more patient than their initially measured baseline discount rates. The finding that patience increases over multiple ITCs has not been previously noted in the temporal discounting literature. In Experiment 1, when choices were presented at participants' previously determined indifference point, immediate rewards were selected in less than 50% of trials. If they were truly at the indifference point, participants should have selected the immediate reward for 50% of trials while under a low working memory load. It was predicted that, over the course of the experiment and with repeated ITCs, participants in Experiment 1 became increasingly more patient. This methodological issue motivated the design of Experiment 2, in which choices were dynamically adapted based on prior behavior.

A second interesting trend that emerged from Chapter 1 was that behavior in one working memory condition carried over into the next condition. This finding has been interpreted in light of a dual-process theory framework, in which cognitive processes that are rapid and automatic are in conflict with those that are slow and deliberative (Kahneman & Frederick, 2002; Stanovich & West, 2000). It may be that for the group who completed the high load condition first, a high WM load may have interfered with deliberative processes, allowing for automatic

judgments to be made. This interpretation supports the hypothesis that a high WM load disrupts control aspects of ITC, leading to more impulsive behavior. Conversely, for the groups that completed the low load condition first, slow, deliberative cognitive processes may have subdued rapid, automatic ones, and this subduing persisted into the second block. These carryover effects were addressed in later studies with the use of a between subjects design.

Meta Analysis of Interference Effects.

In an effort to aggregate and compare the interference findings of the all the studies presented here, a meta-analysis was conducted on the effect sizes of the interference effect across all six studies, with one effect size per study. The total number of participants included in the analysis was 1120. Cohen's d was chosen as the effect size for each study, and conversions to Cohen's d were made from the F -tests, chi-squares, and a t -test (Lipsey & Wilson, 2001). Sampling error variance was calculated for each effect size, and the inverse of the variance was assigned as the weight to the effect size of each study. A random-effects model meta-analysis was conducted using syntax in SPSS 19 for Mac (SPSS, Inc., Chicago, IL). A random-effects model was used because of the differences in sample populations (i.e., some participants were recruited through Princeton University and others through Amazon.com's Mechanical Turk). A Q test of homogeneity was used to examine the variation in effect sizes between studies, and the assumption of homogeneity of variance of the sample was accepted, $Q(5) = 4.75, p = .45$. This suggests that the variance in effect sizes was due to random sampling error alone and that systematic variance is not present in the sample. Results from the meta-analysis support the claim that greater interference with a higher WM load in the N-Back task results in greater

discounting, $d = .33$, 95% CI [.21, .45], $p < .001$, and that the interference effect is a consistent, though relatively moderate, effect across the studies presented in this thesis.

How does a working memory load disrupt control mechanisms?

In Chapter 2, it was hypothesized that a higher working memory load in the N-Back task affects intertemporal choice behavior by either fatiguing or interfering with control mechanisms. The goal of Chapter 3 was to address this question. Specifically, the experiments in Chapter 3 were designed to test two competing hypotheses: that a higher working memory load in the N-Back task either fatigues (mental fatigue due to task length), or interferes (requires higher levels of active maintenance) with cognitive control mechanisms needed for patient ITC decisions. As emphasized earlier, the notion of fatigue here is specific to the length of the N-Back task; fatigue in general has not been ruled out as a potential factor that may influence ITCs.

By increasing the level of load in the N-Back task and by manipulating the number of trials preceding an ITC, Experiments 3 and 4 supported the claim that interference of control mechanisms, rather than fatigue due to task length, may lead to more impulsive choices. These findings are consistent with evidence that dlPFC shows sustained and elevated activity during 2 and 3-Back tasks (Cohen et al., 1997), is critical in inhibiting competing responses (Miller & Cohen, 2001), and is implicated in patient temporal choices (Figner et al., 2010; Hare et al., 2009; McClure et al 2004). Thus, parallel processing of a higher working memory load may interfere with dlPFC's ability to inhibit impulses for immediate rewards, resulting in more impulsive decisions.

What is the role of control in framing effects?

In an effort to provide further evidence for the hypothesis that greater exertion of control is necessary for patient ITCs, the aim the of experiments in Chapter 4 was to leverage the interference manipulation from Chapter 3 in order to examine the role of control processes in paradigms that elicit reduced discounting. Specifically, Experiments 5 and 6 were designed to tease apart whether greater recruitment of cognitive control underlies reduced discounting in acceleration effects (Weber et al., 2007) and in the tag effect (Peters and Büchel, 2010). This hypothesis was tested by crossing high and low interference conditions with acceleration/ delay and episodic/ control conditions.

In Experiment 5, the acceleration effect was successfully replicated by demonstrating that participants chose immediate rewards more often when choices were framed as accelerated rather than delayed. It was also predicted that if greater exertion of control underlies acceleration effects, an interaction would be observed between interference and framing factors. However, this prediction was not supported. Future research should be pointed toward cognitive and neural mechanisms that underlie acceleration effects and query theory. Specifically, an imaging study could be conducted in which delay and acceleration conditions are contrasted in an effort to examine if there is greater activity in control regions during the acceleration condition.

In Experiment 6, the tag effect was successfully replicated by demonstrating that the participants chose immediate rewards less often when choices were tagged with personal future episodic events. It was predicted that if greater exertion of control underlies the tag effect, a high rather than low working memory load would attenuate the effect. However, this prediction was not supported, as the predicted attenuation of the tag effect in the high interference episodic condition was not observed. Rather, it may be the case that in the future episodic conditions, the

hippocampus supports decision-making processes through the mental simulation of future outcomes and provides prefrontal regions with a prediction signal regarding the decision outcome (Johnson et al., 2007; Johnson and Reddish, 2007).

Limitations of the Current Work

One important limitation in this thesis is the source of the carryover or order effects in Experiment 2. Specifically, despite the counterbalanced presentation of low and high load tasks, behavior in the secondary task was determined by the task presented first. Carryover effects may have been due to random responding, boredom, or fatigue. It is of particular concern that participants may have responded randomly, lost interest, or decreased their effort out of frustration with the task. This possibility was addressed here by using a between-subjects design in later studies.

Another limitation of this work is the failure to show an interaction of the interference effect with acceleration (Loewenstein, 1988; Weber et al., 2007) and tag effects (Peters & Büchel, 2010). It was predicted that if control mechanisms underlie effects that have been shown to elicit reduced discounting, then a high WM load in the N-Back task should attenuate those effects due to disruption of control mechanisms. In both Experiments 5 and 6, an interaction was not observed with interference, acceleration, or the tag effect, and our hypothesis was not supported. It is possible that the N-back manipulation was not an appropriately sensitive measure to disrupt mechanisms engaged by this task. As proposed earlier, future studies should be conducted to further examine these promising avenues of research.

Another pending question of the thesis is the question of how, at the neurobiological level, a working memory load affects control processes in ITC. This question cannot be answered with behavioral data, but rather relates to how control is operationalized in these

experiments. In this work, cognitive control mechanisms were operationally defined by assuming that they are processes that are most affected by a high, but not by a low, WM load. This assumption was based on imaging data showing that dlPFC activity is sustained and elevated in 2-Back and 3-Back WM tasks and the role of prefrontal regions in cognitive control (Cohen et al., 2004; Miller & Cohen, 2001). With the use of fMRI, the effects of a high WM load on dlPFC during intertemporal choices can be further investigated. This is an important question that should be addressed in future work, and it is discussed in the next section.

Future Directions

FMRI investigation of the effects of N-Back on ITC performance

This work points toward an important avenue for future research: the evaluation of the neurobiological basis of the interference effect. As outlined in the introduction and elsewhere in this thesis, it is possible that when processing the 2-Back task and temporal decisions in parallel, dlPFC cannot bias processing in favor of the controlled selection of delayed rewards, leading to more impulsive decision-making. This hypothesis has its basis in the role of dlPFC in cognitive control and in the limited capacity of cognitive control (Carter & van Veen, 2007; Miller & Cohen, 2001). One way to test this possibility using fMRI is to employ a design similar to that of Experiment 1. Specifically, participants could perform intertemporal choices while simultaneously performing an N-Back task under high load (2-Back) or low-load (0-Back). As in the experiments presented here, baseline discount rates could be measured and used to engineer ITCs for each participant. Low and high load conditions could be presented in a blocked fashion. Imaging analyses similar to those used by McClure et al., (2004) could be used to identify the β and δ regions. Based on the behavioral findings presented here, as well as earlier imaging

findings (Figner et al., 2010; Hare et al., 2009; McClure et al 2004; 2007), it is predicted that the high load condition would lead to an increase in impulsive responding. Further, after accounting for the direct effects of the WM load (i.e., activity immediately after an N-Back response), activity associated with the δ system (i.e., activity following intertemporal choices) is predicted to show relative decrements during the high load as compared to the low load condition. In the present work, such an approach would provide further evidence about the predicted effects of a high load in the N-Back task on dlPFC during intertemporal choice.

Investigating primary rewards

Future research should examine whether primary rewards are discounted more steeply under greater working memory loads. A working memory load may affect discounting for monetary rewards because specific monetary amounts need to be actively maintained and manipulated in working memory in order to make patient choices. Another possible future line of research could examine whether the effects of a working memory load on intertemporal choice are the same for both primary and monetary rewards. Both conditioned (monetary) and primary, appetitive rewards could be included in the experiment. Given the similarity in neural circuitry for different reward modalities, such as money and juice/water (McClure et al 2004; 2007), a high WM load may lead to greater discounting of both primary and conditioned rewards due to disruption of control mechanisms needed in the selection of long term rewards.

Developmental populations

Another possible application of these findings is to the study of impulsivity in adolescents. Some of the greatest health risks to adolescents come from avoidable and self-inflicted sources (e.g., car accidents, violence, drug and alcohol use, and sexual risk-taking).

Risk-taking and impulsivity decline between adolescence and adulthood due to development of the prefrontal cortex and enhanced capacity for cognitive control (Steinberg, 2008). Since adolescence is characterized by protracted development of PFC, as well as increased risk-taking, an intriguing question is the degree to which an intervention such as promoting future episodic thinking can decrease impulsive behavior in adolescents.

As outlined in Chapter 4, the investigation conducted by Peters and Büchel (2010) only investigated future events that were protracted seven months at most into the future. If thinking about events seven months in the future decreases discounting, then longer-term episodic thinking may result in larger decreases in discounting. It would be worthwhile to examine the possibility that near and long-term future episodic thinking could decrease discount rates in adolescents.

Applications

Impulsivity in intertemporal choice may have serious implications for a number of areas, including issues of health and well-being such as exercising, eating a healthy diet, and refraining from smoking, as well as personal finance questions such as saving for retirement and taking out a mortgage. An approach targeting decision-making mechanisms and the psychological circumstances in which suboptimal judgments arise could also have applications for personal financial decisions.

One possible application of these findings would be an effort to promote “decision hygiene.” The underlying principle of decision hygiene would be to clear working memory of any contents while making important financial decisions, such as those about mortgages. For example, a paragraph could be included at the beginning of mortgage applications that explains

both the long-term implications of the decision and the importance of making decisions while minimal demands are placed on cognitive resources. Additionally, as an example, the applicant could be encouraged to fill out the form in a separate room or after taking a deep breath. The goal of this exercise would be to minimize potential sources of interference with control mechanisms in order to promote optimal long-term financial decisions. There are massive social costs associated with the failure to restrain behavior in the face of temptation, both in the policy and personal spheres. This has been the impetus for the study of which factors impair a person's ability to properly assess the relative merits of immediate versus future rewards.

Conclusion

To review the overall scope of this thesis and the concepts introduced - various neuroimaging findings support the conclusion that greater exertion of cognitive control may underlie more patient intertemporal choices. Given that cognitive control mechanisms are limited capacity resources, it is possible that higher cognitive loads may lead to more impulsive intertemporal decisions. The goal of this thesis was to demonstrate how a simultaneous cognitive load in the N-Back task depletes limited cognitive control resources, resulting in more impulsive behavior. This thesis successfully demonstrated that one type of cognitive load, a high working memory load in the N-Back task, results in more impulsive intertemporal choice behavior. The thesis has also demonstrated that the nature of these effects is to interfere with control mechanisms. On the whole, I hope to have provided evidence for how a cognitive load impacts temporal decision-making and how this information can potentially open up interesting avenues of future research.

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Appendices

Appendix A

Conducting Research on MTurk

MTurk requestors can post any task that can be completed on a computer (surveys, questionnaires, experiments, writing, etc.) and can link to external scripts or experimental tools (e.g., *Qualtrics* or Survey Monkey). MTurk workers browse tasks and are paid once requestors approve the work they completed on the human intelligence task (HIT). Requestors deposit money into online accounts and set compensation rates in advance. Compensation is usually minimal, around \$.10 - \$.30 for a 5-minute task (Buhrmester, Kwang, & Gosling, 2011).

In a sample of 1000 MTurk workers, 69.6% of the US workers reported that their participation on the website was a fruitful way to spend their spare time (Paolacci, Chandler, & Ipeirotis, 2010). Further, Paolacci, Chandler, & Ipeirotis (2010) found that low compensation rates did not impact data quality (e.g., workers paid \$0.02 for a 5 minute survey did not perform differently than workers paid \$0.10), but that it did impact the speed of data collection such that more data was collected per hour when compensation rates were proportionally larger (e.g., when workers are paid \$0.10 as opposed to \$0.02, data is collected about 5 times more quickly by the hour).

Paolacci, Chandler, & Ipeirotis (2010) conducted a study to demonstrate that data generated by MTurk participants did not qualitatively differ from data collected in laboratory settings. Specifically, these authors compared performance of MTurk workers to a more traditional participant population on canonical judgment and decision-making tasks. They found that participants recruited from three populations (MTurk, internet discussion boards, and a subject pool from a Midwestern U.S. university) yielded results consistent with classic judgment

and decision making tasks; namely, they made the conjunction fallacy, the outcome bias, and were more likely to chose a risky course of action when the Asian disease problem (Tversky & Kahneman, 1961) was framed in terms of losses than when it was framed in terms of gains. Moreover, subjects from MTurk had the lowest catch trial failing rate (i.e., responding “*Never*” to the question “*While watching the television, have you ever had a fatal heart attack?*”). Thus these authors concluded that MTurk workers exhibited the classic heuristics and biases and were just as attentive to directions as participants from classic recruitment populations.

Data quality

The two of the main concerns that arise regarding data collection on MTurk are: 1) since MTurk workers are paid such small amounts and are unsupervised, they may not take tasks seriously; and 2) individual respondents may provide many separate responses to the same study. The first concern is solved by including “catch trials” that identify when participants fail to pay close attention and instructional manipulation checks that identify whether subjects have thoroughly read the instructions (IMC; Oppenheimer, Meyvis, & Davidenko, 2009). The IMC can either be used as exclusion criteria, or a researcher can actively intervene on participants by forcing them to reread instructions after failing the IMC by prompting them with “try again” until they reread instructions carefully enough to pass.

To address the second concern above regarding multiple responses from a single individual, each worker on MTurk is assigned a unique Worker ID and experimenters can therefore identify workers who have previously taken part in their experiment. Basic programming can be used to specify which workers can complete the HIT. In order to receive payments, MTurkers must provide Amazon.com with a Social Security Number, which helps

ensure that a single worker cannot complete a study using multiple Worker IDs and still get paid for their participation. Finally, a self-report question can be included at the end of the experiment asking participants whether they have already completed a similar version of the task.

Appendix B

Instructional manipulation check

Recent research on decision-making shows that choices are affected by context. Differences in how people feel, their previous knowledge and experience, and their environment can affect choices. To help us understand how people make decisions, we are interested in information about you. Specifically, we are interested in whether you actually take the time to read directions; if not, some results may not tell us very much about decision making in the real world. To show that you have read the instructions, please ignore the question below about how you are feeling and instead check on the "none of the above" option as your answer. Thank you very much.

- | | | |
|----------------------------------|------------------------------------|---|
| ☐ Interested | ☐ Hostile | ☐ Nervous |
| ☐ Distressed | ☐ Enthusiastic | ☐ Determined |
| ☐ Excited | ☐ Proud | ☐ Attentive |
| ☐ Upset | ☐ Irritable | ☐ Jittery |
| ☐ Strong | ☐ Alert | ☐ Active |
| ☐ Guilty | ☐ Ashamed | ☐ Afraid |
| ☐ Scared | ☐ Inspired | ☐ None of the above |

Appendix C

Monetary-Choice Questionnaire

For each of the next 27 choices, please indicate which reward you would prefer: the smaller reward today, or the larger reward in the specified number of days.

1. Would you prefer \$54 today, or \$55 in 117 days?

☐ smaller reward today

☐ larger reward in the specified number of days

2. Would you prefer \$55 today, or \$75 in 61 days?

☐ smaller reward today

☐ larger reward in the specified number of days

3. Would you prefer \$19 today, or \$25 in 53 days?

☐ smaller reward today

☐ larger reward in the specified number of days

4. Would you prefer \$31 today, or \$85 in 7 days?

☐ smaller reward today

☐ larger reward in the specified number of days

5. Would you prefer \$14 today, or \$25 in 19 days?

☐ smaller reward today

☐ larger reward in the specified number of days

6. Would you prefer \$47 today, or \$50 in 160 days?

☐ smaller reward today

☐ larger reward in the specified number of days

7. Would you prefer \$15 today, or \$35 in 13 days?

☐ smaller reward today

☐ larger reward in the specified number of days

8. Would you prefer \$25 today, or \$60 in 14 days?

☐ smaller reward today

☐ larger reward in the specified number of days

9. Would you prefer \$78 today, or \$80 in 162 days?

☐ smaller reward today

☐ larger reward in the specified number of days

10. Would you prefer \$40 today, or \$55 in 62 days?

☐ smaller reward today

☐ larger reward in the specified number of days

11. Would you prefer \$11 today, or \$30 in 7 days?

☐ smaller reward today

☐ larger reward in the specified number of days

12. Would you prefer \$67 today, or \$75 in 119 days?

☐ smaller reward today

☐ larger reward in the specified number of days

13. Would you prefer \$34 today, or \$35 in 186 days?

☐ smaller reward today

☐ larger reward in the specified number of days

14. Would you prefer \$27 today, or \$50 in 21 days?

☐ smaller reward today

☐ larger reward in the specified number of days

15. Would you prefer \$69 today, or \$85 in 91 days?

☐ smaller reward today

☐ larger reward in the specified number of days

16. Would you prefer \$49 today, or \$60 in 89 days?

☐ smaller reward today

☐ larger reward in the specified number of days

17. Would you prefer \$80 today, or \$85 in 157 days?

☐ smaller reward today

☐ larger reward in the specified number of days

18. Would you prefer \$24 today, or \$35 in 29 days?

☐ smaller reward today

☐ larger reward in the specified number of days

19. Would you prefer \$33 today, or \$80 in 14 days?

☐ smaller reward today

☐ larger reward in the specified number of days

20. Would you prefer \$28 today, or \$30 in 179 days?

☐ smaller reward today

☐ larger reward in the specified number of days

21. Would you prefer \$34 today, or \$50 in 30 days?

☐ smaller reward today

☐ larger reward in the specified number of days

22. Would you prefer \$25 today, or \$30 in 80 days?

☐ smaller reward today

☐ larger reward in the specified number of days

23. Would you prefer \$41 today, or \$75 in 20 days?

☐ smaller reward today

☐ larger reward in the specified number of days

24. Would you prefer \$54 today, or \$60 in 111 days?

☐ smaller reward today

☐ larger reward in the specified number of days

25. Would you prefer \$54 today, or \$80 in 30 days?

☐ smaller reward today

☐ larger reward in the specified number of days

26. Would you prefer \$22 today, or \$25 in 136 days?

☐ smaller reward today

☐ larger reward in the specified number of days

27. Would you prefer \$20 today, or \$55 in 7 days?

☐ smaller reward today

☐ larger reward in the specified number of days

Appendix D

Personal Future Events

Please briefly describe a personal future event you have planned in 3 weeks (e.g., vacations, weddings, parties, courses and so forth).

How do you feel overall about this event?

Very Negative	Negative	Somewhat Negative	Neutral	Somewhat Positive	Positive	Very Positive
☐	☐	☐	☐	☐	☐	☐

How excited are you about this event?

Very Indifferent	Indifferent	Somewhat Indifferent	Neutral	Somewhat Excited	Excited	Very Excited
☐	☐	☐	☐	☐	☐	☐

How relevant is this event to you personally?

Very Irrelevant	Irrelevant	Somewhat Irrelevant	Neutral	Somewhat Relevant	Relevant	Very Relevant
☐	☐	☐	☐	☐	☐	☐

Sample item from the Personal Future Events questionnaire.