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Time for a change? Brain activity and behavioral performance reveal different dynamics at short, intermediate, and long delay intervals during a delay discounting task

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by

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The members of the Honors Thesis Committee appointed
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ABSTRACT

Time for a change? Brain activity and behavioral performance reveal different dynamics at short, intermediate, and long delay intervals during a delay discounting task

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In our day to day lives, the ability to make goal-oriented decisions plays a crucial role in both our work and social lives. Therefore, researchers have examined how factors such as a varying reward or delay may affect decision making. One's performance when making intertemporal choices, decisions made between a smaller and sooner (SS) reward and a larger and later (LL) reward, are often examined to study these factors. Although time and reward magnitude are important dimensions when individuals make decisions during delay discounting, little is known about the relationship between time perception, reward magnitude, and underlying neural mechanisms. To address this gap in literature, participants completed a modified delay discounting task during fMRI with stimuli that included fluctuating reward and delay values. An exploratory factor analysis using behavioral data identified three categories of delays and reward values that were used to create brain contrasts. In these comparisons, the middle frontal gyrus and cingulate gyrus seemed to be more involved when choosing rewards of greater magnitude while the medial frontal gyrus and insula were found to be more active for longer delays. Our results suggest that delay and reward determination are handled by separate neural networks.

KEYWORDS: intertemporal choice, fMRI, time perception, reward magnitude

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1. Introduction

Each day, individuals are tasked with making a variety of different decisions. These choices range from low caliber decisions such as what to have for breakfast to more life changing ones like buying a house. To make these selections, humans are constantly weighing the pros and cons of each outcome. Living in a society with rules and regulations, the ability to properly make goal-orientated choices is important in forming productive relationships with others, holding down a job, and having the money to purchase the goods needed to survive. Since proper decision-making is a key trait in one's life, much research has been done looking at the different factors that affect one's capacity to choose. Impulsivity is one such factor that asserts its influence on an individual's decision making ability in a number of different areas in their life including: financial planning (Banks et al., 1998); (Thompson et al., 1983), choice of diet (Shapiro, 2005), sexual risk-taking (Clift et al., 1993), and even political policy making (Berns et al., 2007). Properly understanding the hold that impulsivity has over a person's decision making becomes more relevant considering the high level of impulse control deficiencies in numerous pathological conditions such as borderline and antisocial personality disorders (Stein et al., 1993); (Stein et al., 1995), as well as the general likelihood of engaging in criminal behavior (Eysenck & McGurk, 1980). In these situations, impulsivity influences one's process for making intertemporal choices. Intertemporal choices involve an individual choosing between a smaller and sooner (SS) reward or a later and larger (LL) reward (Frederick et al., 2002). To examine intertemporal choice, a

delay discounting paradigm is often utilized. People are said to display delay discounting behavior when they repeatedly show a propensity for an SS reward to an LL reward when making an intertemporal choice. This research will examine intertemporal choice using fMRI and a novel delay discounting task to provide a more in-depth map of how intertemporal decisions activate the brain.

1.1. Brain Activation During Intertemporal Choices

Steep and excessive discounting has been exhibited in many problematic behaviors in both healthy populations and populations with self-control deficiencies (Ainslie, 1975); (Frederick et al., 2002). Historically, intertemporal choices have been studied in the fields of economics and psychology. Neuroscience is the most recent entrant into this interdisciplinary topic, bringing with it the possibility to see how intertemporal choices activate the brain. To date, research generated by neuroscientists has been in the form of functional neuroimaging studies employing region-of-interest (ROI) analyses, which have identified different brain regions responsible for future-based LL choices and present-focused SS choices. Specifically, the mesolimbic dopamine system has been associated with immediate rewards, while the lateral prefrontal regions and the posterior parietal cortex are shown to respond to future rewards (McClure et al., 2007).

These findings have been used to support the creation of a two-component model of intertemporal choice. In this model, one system is said to control the weighing of rewards offered in an immediate time frame (known as the beta system), while the other is said to weigh rewards offered at all delays (the delta system; (Laibson, 1997)). These studies helped to establish a basis for understanding how intertemporal choices occur;

however, they were confronted by findings from Kable and Glimcher (2007) that exhibited activation of the mesolimbic projection regions (nucleus accumbens and medial prefrontal cortex) in correlation to a combination of the magnitude and delay of a reward. Their conclusion from these results was that only a single system in the brain is involved in making intertemporal choices, and it responds to a combination of magnitude and delay information to hyperbolically discount future rewards. In an effort to make sense of these contrasting results, Ballard and Knutson (2009) created a novel delay discounting task that they hoped would allow them to determine if independent neuronal substrates would activate in response to the magnitude and delay of a reward before a final choice was made. Their results showed that the nucleus accumbens was sensitive to magnitude information and the lateral cortical regions were sensitive to delay information. In turn, these findings provided initial evidence pointing to these constructs resulting from separate neural pathways.

With delay and reward magnitude hypothesized to enlist different neuronal pathways when making intertemporal choices, further research has been done to determine how one's perception of time and reward value may factor into these differences. One insight for this line of inquiry comes from previous studies that have suggested an altered sense of time as the cause for the steep discounting behavior observed in more impulsive individuals (i.e. an altered perception of delay) (Barkley et al., 2001); (Barratt, 1983); (Reynolds & Schiffbauer, 2004). Another insight comes from knowledge on how individuals from different socioeconomic backgrounds may perceive the value of a monetary reward.

1.2. Modeling Intertemporal Choices

Looking back on the research done in the fields of psychology and economics, a large part of their literature has involved modeling intertemporal choices using a functional model. These value functions often derive from monetary intertemporal choice data and are typically expressed in terms of a discounting curve over time. Two generally accepted models predominate the literature and they are the exponential discounting model and the hyperbolic discounting model. Many studies have involved trying to fit discounting behavior in a variety of different conditions to one of these models (Green & Myerson, 2004); (Kirby & Maraković, 1995); (Loewenstein & Thaler, 1989); (Mazur, 1987). The exponential model is calculated as

$$\boldsymbol{V = Ae^{-kD}}$$

where V signifies the present value of the delayed reward (otherwise known as the indifference point), A is the amount of the delayed reward, D is the delay, and k is the discounting rate parameter. However, this model has often seen pushback due to the inconsistencies in its ability to represent discounting behavior in animal (Ainslie, 1975) and human (Kirby & Herrnstein, 1995) research. For example, individuals may prefer an SS reward when immediately offered the choice; yet, when delaying the outcome of both rewards equally, subjects will switch their preference to the LL reward (Kirby & Herrnstein, 1995). To better account for these irregularities, a hyperbolic model, such as the following, has been suggested (Mazur, 1987):

$$\boldsymbol{V = A/(1 + kD)}$$

Hyperbolic functions describe a discounting pattern that is steeper at short delays than long delays and in this manner is better able to reflect observed behavioral data in most scenarios. The different curvature seen in this hyperbolic function over time echoes

results seen in the fMRI study done by McClure et al. (2004) that demonstrated a more impulsive beta system in charge of SS decisions and a more patient delta system that handles LL choices.

More recent findings (Figner et al., 2010) suggest that although individuals often prefer SS options, LL choices will still get chosen in some cases due to the activation of a self-control mechanism that is controlled by the left Lateral Prefrontal Cortex (lLPFC). This view states that the lLPFC is not just a part of the more patient delta system that has been presented in research; rather, it is an independent neuro-substrate in regulating intertemporal choice. This finding has led us to conduct this research, as we believe that in cases of rewards involving exceedingly long delays (e.g. numerous years), the delta system may be restricted by reaching its cognitive and computational limit. As a result, the lLPFC (and possibly other brain areas) may play a bigger role for choosing LL options.

The above converging behavioral and neuroimaging findings suggest that a unitary discounting function may not be a psychological reality. In this study, we propose a Tri-phasic Delay Discounting hypothesis that suggests delay discounting as a function of temporal distance consists of three phases: (1) initial and short delays from the present time to hours or days in the future, (2) foreseeable and tractable delays of weeks to a few years, and (3) distal long delays of more than multiple years. The third component of this novel hypothesis (diminished sensitivity), which is not included in the two system hypothesis proposed by McClure et al. (2004), accounts for the flattened portion of delay discounting associated with distant and long delays and is expected to be a result of cognitive limitation (see Figure 1). For example, cognitive limitation is often

evident in the average person's inability to properly compute compound interest. Another goal of this research is to use our novel delay discounting task to take what is already expressed in the literature about delay and reward magnitude and determine if we are able to see different neuronal activation regions using reward and delay magnitude as variables. While it has been found that varying the reward and delay, as well as one's perception of this variation, may result in differential activation, little is still known about how these systems work together to form a complete network when making intertemporal choices.

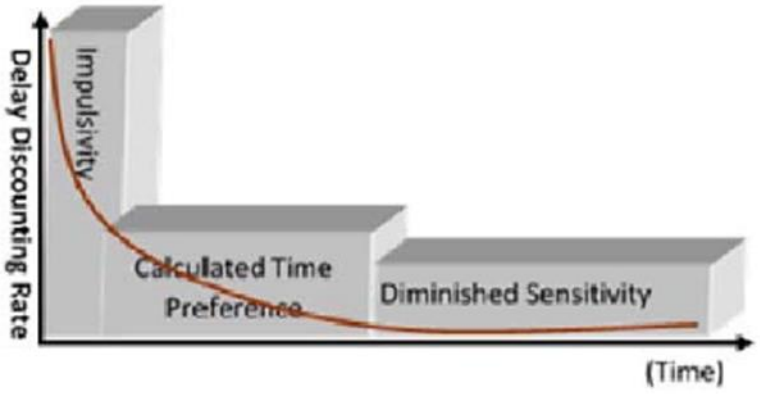


Figure 1. Hypothesized delay discounting curve. Our hypothesis predicts a tri-phasic delay discounting curve, with a hyperbolic function best representing the initial discounting rate, but an exponential function fitting the latter time points.

2. Hypotheses and Predictions

2.1. Behavioral Hypothesis

The current study will examine how what has previously been learned about delay discounting tasks extends into time scales previously unexplored. Behaviorally, we envision that participants will perform congruently to other studies when it comes to intertemporal choices that involve an earlier time base, demonstrating behavior that can be best modeled by a hyperbolic discounting curve. Following our novel tri-phasic

discounting hypothesis, we envision that when the temporal delay becomes much later, behavior will start to follow more of an exponential form due to individuals reaching their computational limits when it comes to judging value.

2.2 Neuroimaging Hypotheses

Hypothesis 2a. We propose that different areas of brain activation will be involved when choosing LL opposed to SS rewards. Numerous fMRI delay discounting studies have been conducted in the past demonstrating this effect and we can use these studies to confirm that similar areas are active for our delay discounting using novel stimuli. From previous studies, LL decisions are expected to be associated with higher activation of the medial orbitofrontal cortex (mOFC) (Cohen et al., 2011);(Sellitto et al., 2010);(Sellitto et al., 2011) and the dorsolateral prefrontal cortex (dlPFC) (Hutcherson et al., 2012). Prefrontal cortex regions play a large role in executive control and delaying gratification, which support these findings. Additionally, it has been predicted that the posterior cingulate gyrus is involved with choosing larger rewards throughout all time intervals (Wittmann & Paulus, 2008); therefore, this region should be active when contrasting between small versus large rewards, but not between different delay periods. Another probable area of activation is the insula. Previous results have shown insular activation in decision making studies on risk-taking (Ernst et al., 2002) and anticipation of rewards (Critchley et al., 2001). Wittmann and Paulus (2008) recorded findings that suggest specific activation in the posterior part of the insula during LL rewards while ventroanterior parts of the insula and striatum are more active during SS reward selection. For SS decisions, activation is expected in the ventral medial prefrontal cortex (vmPFC) (Hare et al., 2009).

Hypothesis 2b. Our novel Tri-Phasic Delay Discounting Hypothesis predicts that behavioral results could best be predicted by a three-phase discounting function. We hypothesize that each phase of this Triphasic function will also elicit neuronal activation in specific and separate brain areas. To determine separate activation across different time clusters, our delay discounting task involved questions where the delay ranged from 1 day to 20 years (**s**ee methods). Once participant responses were collected, an exploratory factor analysis was used to collapse across reward value and identify any delay periods that clustered together (**s**ee methods). Three distinct time periods were found and labeled short (days to months), intermediate (1, 2, and 5 years), and long (10 or 20 years). We hypothesize that brain activation patterns over the three time periods, which would correspond to the three phases in our proposed function, are distinguishable. Predicted activation from responses to questions in the short time period should involve reward-pleasure related brain areas such as ventral striatum and medial forebrain structures, including insula, caudate, putamen, and medial prefrontal cortex (Knutson, Fong, et al., 2001); (Knutson et al., 2000). Intermediate time period activation is likely to be observed in the cognitive control areas such as the dorsolateral prefrontal cortex (dlPC) (McClure et al., 2007);(Essex et al., 2012). Activation during long, extended delays is more difficult to determine with little previous research; therefore, non-specific higher cortical activations (Jaeggi et al., 2007) are predicted during this phase.

Hypothesis 2c. The magnitude of the delayed reward is also expected to result in specific neuronal activation. We predict that activity in the nucleus accumbens, medial prefrontal cortex, and posterior cingulate cortex will increase with the magnitude of reward as seen in previous work (Ballard & Knutson, 2009). Some of these brain areas may be active as

a result of a combination of differing delays and magnitudes; however, the nucleus accumbens has been found to respond only to fluctuations in future reward magnitude. These regions align with current predictions that the mesolimbic circuits are responsible for encoding the magnitude of anticipated future rewards (Knutson, Adams, et al., 2001); (Knutson & Cooper, 2005). By using a factor analysis, we are able to collapse across time delays to identify monetary amounts that cluster together based upon the participant's perception. These groups were labeled as small ($50), medium ($500, $5,000), and large ($500,000) monetary reward groups (see methods). Identifying our groupings in this manner allows us to determine the assignment of each monetary reward amounts based upon participant responses rather than our perception of what qualifies as a small versus medium/large money reward.

3. Method

3.1 Participants

Forty-three right-handed native English-speaking adults (28 females; mean age 21.91 ± 5.16 age range 18 – 37 years of age) participated in this study. Exclusion criteria included: (a) current pregnancy or lactation; (b) history of head injury or neurologic disorders; and (c) any contraindications to MRI based on a safety screening. Participants provided written informed consent for a protocol approved by the Institutional Review Board of the University of South Dakota.

3.2 Assessment Instruments and Tasks

Participant interviews, scale administration, and delay discounting tasks first took place at an initial meeting, which was on a separate day from the fMRI study. This allowed for a complete description of the fMRI study procedures, screening for

contraindications to MRI, and the collection of scale and delay discount task responses to establish stability in delay discount rate and scale responses over time; participants completed the same scales and delay discounting tasks during the fMRI study. Participants were administered a demographic questionnaire to assess age, gender, and handedness. The Domain Specific Risk Taking Scale (DOSPERT-7); (Wang et al., 2016) was used to assess individual differences in both evolutionarily typical and modern risk taking propensity across seven domains, including cooperation/competition, safety, reproduction, natural/physical risk, financial risk, and gambling. The Barratt Impulsiveness Scale version 11 (BIS-11); (Patton et al., 1995), was used to assess the personality/behavioral construct of impulsiveness. Participants also completed two versions of a delay discounting task.

To encourage accurate realistic responses, delay discounting tasks were presented as a (simulated) sealed auction, a task adapted from Kirby and Maraković (1995) and Kirby and Santiesteban (2003). In one version, participants were asked to bid the least amount of money they would be willing to accept today in exchange for receiving a delayed larger reward, without knowledge of the bids of the other participants. In a second version of the sealed auction, participants were told to bid the most they would be willing to pay today in order to receive a larger reward after a delay. These accept-today and pay-today procedural variations have been found to lead to no differences in discount rates generated (Kirby & Santiesteban, 2003). Participants completed a total of 52 pay-today and 51 accept-today trials, using four monetary rewards: $50; $500; $5,000; $500,000 and 13 time delays: 1 day, 2 days, 3 days, 1 week, 2 weeks, 1 month, 2 months, 6 months, 1 year, 2 years, 5 years, 10 years, 20 years. Participants were instructed that

there would be one winner for each of the two delay discounting auction games, and that the winner would be the person who bid the true value of the delayed reward as determined by a formula. For the delay discounting tasks, we used real monetary rewards—as opposed to hypothetical rewards—to encourage realistic responses and increase the generalizability of results (e.g. (Kirby & Maraković, 1995); (Xu et al., 2016)). To increase the external validity of the auction game, participants were asked to write their preferred mailing address on a blank envelope, which would be used to send their monetary reward should they win the auction. Participants were not informed when the study would be complete, nor the value of the monetary reward in order to reduce bias associated with subjective costs associated with the delay or reward value. Upon completion of the study, two participants were randomly selected as "winners" of the auction game and mailed a $25 money order. Altogether, using a real monetary reward, a sealed bid auction, and two types of delay discounting trials discouraged underbidding or overbidding, minimized bias and the subjective cost associated with the delayed reward for winning, and encouraged realistic responses.

3.2.1 Accept-Today Delay Discounting Task. The accept-today delay discounting task was structured so that the participant decided the amount of money they would need to forgo a smaller amount of money to be received today in order to receive a larger monetary reward in the future. Instructions were presented on the screen as follows: "For the next series of questions, you will play an auction game against other participants of this study. In the next task, you will be able to win a small amount of real money, based upon the auction results. There will be approximately 32 participants in this study. All of you will participate in a sealed auction. The winner of the auction will receive a

money reward sent by mail after the study is finished. Therefore, you should choose your bids carefully. The easiest way to decide how much to bid is to ask yourself what is the LEAST you would be willing to accept. In each choice task, you will indicate the LEAST amount of money that you would accept for a larger future reward by giving up the smaller present reward."

In exchange for $500 today, the LEAST return I would be willing to accept in 2 months is $_____.

3.2.2 Pay-Today Delay Discounting Task. In contrast, the pay-today task asked participants to forego a larger monetary reward to be received after a delay in order to receive a smaller reward today. These questions were also structured as an auction, with the following instructions:

"For the next series of questions, you will play an auction game against other participants of this study. In the next task, you will be able to win a small amount of real money, based upon the auction results. There will be approximately 32 participants in this study. All of you will participate in a sealed auction. The winner of the auction will receive a money reward sent by mail after the study is finished. Therefore, you should choose your bids carefully. The best strategy is to bid exactly what the future reward is worth to you. The easiest way to decide how much to bid is to ask yourself what is the MOST you would be willing to pay for the guaranteed future reward. In each choice task, you will indicate the MOST amount of money that you would pay today in order to receive a larger future reward."

An example of a pay-today trial was:

In exchange for $500 in 2 months, the MOST I would be willing to pay is $_____ today.

3.3 Procedure

3.3.1 Initial Meeting. Following informed consent, participants completed a demographic questionnaire, MRI screening form, DOSPERT-7 scale, BIS-11 scale, and the 52 pay-today and 51 accept-today delay discounting trials administered with an online survey software tool, PsychData, and presented in counterbalanced order to control for order effects. Participants were reimbursed with either university course credit or $20 in cash on the day of the study. The initial meeting took approximately 60 minutes.

Participants who were interested in the fMRI study, and who were not excluded (see exclusion criteria), participated in the fMRI study. This resulted in 33 (19 females; mean age 22.91 ± 5.51; age range 18 – 37 years of age) of the original 43 participants undergoing fMRI on average 16.39 ± 12.93 days (range 0 – 45 days) from the initial meeting.

3.3.2 fMRI Testing Session. On the day of the fMRI study, participants again provided written informed consent, and were reimbursed $40 for their time and travel to the scanning location. Participants completed the DOSPERT-7, BIS-11, and 51 pay-today and 52 accept-today delay discounting trials while fMRI was performed. Tasks were presented on a 30-inch LCD screen (Invivo, Gainesville, FL) that participants could view using a single reflection mirror box affixed to the head-coil. Behavioral responses were collected with an MR-compatible button response box (Lumina LP-400, Corporation, San Pedro, CA), which was affixed to the participant's wrist via a Velcro strap to ensure minimal movement during the study. A graphic representing this set-up is

shown in Figure 2. Stimulus presentation and data recording were accomplished using a dedicated PC running custom software (LabVIEW 2015; National Instruments, Austin, TX, USA).

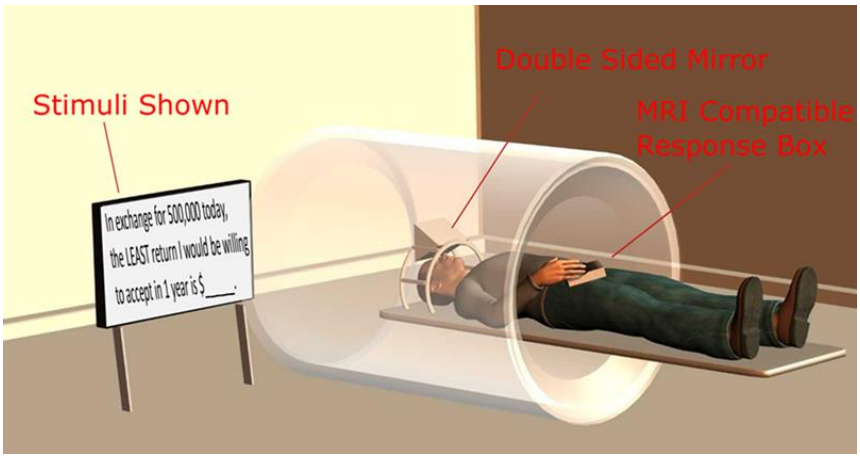


Figure 2. How participants were positioned in the scanner for our delay discounting task

For the delay discounting tasks, the response box was programmed so that a button press corresponding to the right-hand index-finger (left button) decreased the amount displayed, while a button press with the right-hand middle finger (right button) increased the amount displayed. The amount decreased and increased by a single button press was scaled at 1% of the value used in the trial. For example, for delay discounting trials with $50, each button press increased or decreased the value by 50 cents; for trials with $500 a button press increased or decreased the value by $5; for trials with $5,000 a button press increased or decreased the value by $50; and for $500,000 trials a button press increased or decreased the value by $5,000. Changes in response values were updated on the display with each button press. Participants were given 14 seconds to respond, with the value at the end of this period serving as their trial response (Figure 3).

3.3.3 Image Acquisition and Pre-Processing. Conventional Blood Oxygen Level Dependent (BOLD) imaging techniques were used on a 3-Tesla whole-body Siemens Skyra scanner (Erlangen, Germany) and integrated 20–channel birdcage radio frequency coil. Functional MRI volumes were collected using a T2*-weighted, single-shot, gradient-echo, echo-planar imaging acquisition sequence [TR: 2000 ms; TE: 30 ms; slice thickness: 4 mm; gap thickness: 0 mm; in-plane resolution: 3.4375 mm × 3.4375 mm; matrix size: 64 × 64 mm; FOV: 220 × 220 mm; flip angle: 90°]. Acquisition was angled along the plane of the anterior and posterior commissures. We collected a total of 520 volumes across three functional runs (180, 169, and 171 volumes) for the accept-today and the pay-today delay discounting tasks. After functional imaging, a high resolution T1-weighted Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE) was collected for each participant [TR: 1900 ms; TE: 2.13 ms; slice thickness: 0.9 mm; gap thickness: 0 mm; in-plane resolution: 0.9375 × 0.9375 mm; matrix size: 256 × 256 mm; FOV: 240 × 240 mm; flip angle: 9°].

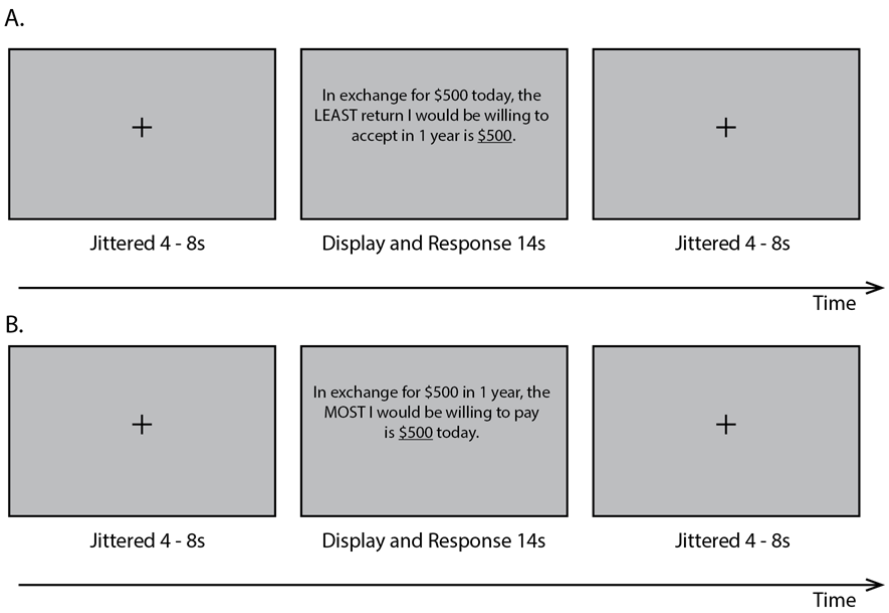


Figure 3. Timeline of one trial of the delay discounting tasks, which utilized an event-related fMRI design with trial-onset asynchrony. A. Accept-today delay discounting task. B. Pay-today delay discounting task. Written instructions for the auction game were presented at the start of each functional run. Responses were made with a button response device. Each button press would increase or decrease the displayed underlined value by 1%. In this case, a left button press would decrease the underlined value by $5, while a right button press would increase the underlined value by $5 ($500 x .01 = $5). Participants completed 51 pay-today and 52 accept-today trials across 6 functional runs. Tasks were counterbalanced to control for order effects. T1-weighted images were taken at the completion of the delay discounting tasks. $N = 33$

BrainVoyager (Brainvoyager 20.6, Brain Innovations, Maastricht, the Netherlands) was used for all imaging analyses. Functional data preprocessing steps included slice scan time correction, 3D motion correction, and temporal high pass filtering. Slice scan time correction was performed using cubic spline interpolation based on information about the TR (2000 ms) and the order of the slice scanning (interleaved slice order). 3D motion correction (trilinear estimation and sinc resampling) was carried out to detect and correct small head movements by spatially aligning all volumes within a functional run to the first recorded volume (rigid body transformation). A temporal high pass filter was used to remove frequencies lower than two cycles per time course.

Anatomical data underwent brain extraction and inhomogeneity correction. Anatomical and functional data were spatially normalized to the Talairach coordinate system (Tournoux, 1988) with an intensity alignment using a multi-scale approach. After registering the functional and anatomical data, spatial smoothing using a Gaussian kernel with a full-width at half maximum (FWHM) of 8 mm was also performed.

Functional runs with head motion greater than 1˚ or 1 mm of rotation or translation, respectively, were removed from further analyses. This resulted in the removal of nine (out of 99) functional runs for the pay-today task, and eight (out of 99) functional runs for the accept-today task.

3.3 Behavioral Data Analysis

Participant responses to the pre-scan survey questions as well as their responses in the scanner were collected using IBM SPSS Statistics Version 20 software. This software was then used to carry out the statistical analyses done with the data, which included a factor analysis to determine both our time and magnitude clusters. By making use of factor analysis and collapsing across reward amounts, we were able to find the delays that naturally clustered together based upon how participants responded to the questions rather than by our own intuition. This meant that from one clustered group of delays to another, there were observable differences in participant responses regarding how much money they would be willing to accept in the future or pay today. The delay clusters found were (days to months); (1, 2, and 5 years); and (10 or 20 years). We labeled these clusters as short, medium, and long respectively. An almost identical procedure was used to find the monetary rewards that group together based upon responses regardless of the delay period. Three clusters were found for monetary rewards

which were ($5), ($500 to $5,000), and ($500,000). These clusters of rewards were labeled as small, medium, and large.

3.4 Functional Imaging Data Analysis

Data were analyzed using a random-effects model, implemented with a two-level procedure. Following preprocessing, single-subject fMRI data were modeled in a general linear model (GLM) by a design-matrix comprised of onsets and durations for each event for each functional run of the pay-today and accept-today tasks. A total of nine predictors were defined, based on the results of a factor analysis (see Table 1); each predictor was convolved with a two-gamma hemodynamic response function (HRF); (Boynton et al., 1996). An uncorrected p-value of 0.001 was first used, followed by cluster-level statistical thresholding to $p = 0.05$ to control for multiple comparisons. This cluster thresholding approach (Forman et al., 1995) is recommended as a method to reduce false positives, increase localization, and aide in the accurate interpretation of fMRI results (Woo et al., 2014).

4. Results

4.1 Behavioral Results

The delay discounting questions that were presented to participants in the scanner were identical to those they saw in the pre-scan questionnaire. Having participants respond twice to these questions gave us the opportunity to assess whether any irregularities would result from a change in environment. Upon comparing participant answers in SPSS, no significant changes were found in responses between the pre-scan and in-scan questions.

Table 1. The nine different predictors found from our fMRI data using factor analysis

Reward	Delay	Predictors
$50 (Small)	Short (Days to Months)	SmallShort
$50 (Small)	Intermediate (1,2,5 years)	SmallIntermediate
$50 (Small)	Long (10 to 20 years)	SmallLong
$500 to $5000 (Medium)	Short (Days to Months)	MediumShort
$500 to $5000 (Medium)	Intermediate (1,2,5 years)	MediumIntermediate
$500 to $5000 (Medium)	Long (10 to 20 years)	MediumLong
$500,000 (Large)	Short (Days to Months)	LargeShort
$500,000 (Large)	Intermediate (1,2,5 years)	LargeIntermediate
$500,000 (Large)	Long (10 to 20 years)	LargeLong

4.2 Neuroimaging Results

The purpose of our neuroimaging data was to look at brain activity differences that occur when participants make intertemporal choices under different time frames and with varying reward values. All fMRI scans were analyzed using Brain Voyager software. To investigate brain activation, the questions that statistically clustered together based upon the delay period were used to make contrasts in Brain Voyager that compared brain activity occurring during answers to *short* questions vs *long* questions, *short* vs *intermediate*, and *intermediate* vs *long*. As an example of these contrasts, the *long vs short* grouping would display areas of the brain that were active across all participants whenever they were presented with a question when the delay was long (10 to 20 years) compared to when the delay was short (days to months). Also, this contrast displays areas of the brain more active when the delay is short compared to when the delay is long, but uses a different identifier (color, negative value). Significant areas of

activation found in these contrasts are displayed in Table 2 and Figure 4. In the long vs short delay contrast, activation was seen in the fusiform gyrus, culmen, medial frontal gyrus, precentral gyrus, insula, and superior temporal gyrus during answers to long delay questions, while activity in the cuneus was observed during short delay questions. The intermediate vs short delay contrast showed activity in the middle occipital gyrus, culmen, medial frontal gyrus, precentral gyrus, insula, and inferior occipital gyrus during intermediate periods, while short delay questions only showed cuneus activation. A contrast was also attempted for the long vs intermediate time periods; however, no significant differences in activation were found between these delays.

In a similar fashion, activation contrasts were also created for varying reward magnitudes. These contrasts included the pairings *large* vs *small*, *medium* vs *small*, and *large* vs *medium* reward values (corresponding to the statistical groupings determined previously). The large vs small contrast showed activation in the precuneus, middle frontal gyrus, cingulate gyrus, and middle frontal gyrus in response to large rewards. Small rewards caused activation in the inferior parietal lobule, precentral gyrus, and inferior parietal lobule. The medium vs small contrast displayed medium sized rewards eliciting activation in the cuneus and middle frontal gyrus, whereas small rewards resulted in activation in the inferior parietal lobule, postcentral gyrus, and insula. The last contrast created between reward values was large vs medium, and it showed activation in the angular gyrus when large reward questions were asked. These results are summarized in Table 3 and Figure 5.

Table 2. Brain contrasts created for differing delay periods. Positive t-values are more active during + conditions. Negative t-values were more active during – conditions. *Note*. Abbreviations R = Right; L = left; BA = Brodmann area; NOV = number of voxels. Peak voxel, Brodmann area, and Talairach coordinates are for the peak voxel. All activation sites reached $p < .001$ after cluster thresholding corrections. One voxel is equal to 3 mm^3. $N = 25$.

Peak Voxel	Side	BA	Talairach Coordinate			NOV	*t*
			x	y	z		
			Intermediate+ Short-				
Cuneus	R	17	3	-79	10	3948	-4.944561
Middle Occipital Gyrus	R	37	49	-64	-8	8781	8.169078
Culmen	R	-	12	-49	-17	10071	7.213074
Medial Frontal Gyrus	L	6	-3	-10	52	3207	6.141321
Precentral Gyrus	L	4	-30	-25	49	16885	7.928279
Insula	L	13	-42	-7	13	1437	5.544353
Inferior Occipital Gyrus	L	18	-45	-79	-8	2052	5.74411
Peak Voxel	Side	BA	Talairach Coordinate			NOV	*t*
			x	y	z		
			Long+ Short-				
Cuneus	R	17	3	-82	13	10210	-4.977944
Fusiform Gyrus	R	19	42	-67	-5	4877	6.339715
Culmen	R	-	15	-46	-17	6599	8.782126
Medial Frontal Gyrus	L	6	-6	-13	55	1994	5.087734
Precentral Gyrus	L	4	-30	-28	52	12510	6.900496
Insula	L	13	-42	-4	13	2423	5.833056
Superior Temporal Gyrus	L	41	-42	-34	16	2952	4.729481

Table 3. Brain contrasts created for differing reward magnitudes. Positive t-values are more active during + conditions. Negative t-values were more active during – conditions. *Note*. Abbreviations R = Right; L = left; BA = Brodmann area; NOV = number of voxels. Peak voxel, Brodmann area, and Talairach coordinates are for the peak voxel. All activation sites reached $p < .001$ after cluster thresholding corrections. One voxel is equal to 3 mm^3. $N = 25$.

Peak Voxel	Side	BA	Talairach Coordinate			NOV	*t*
			x	y	z		
			Medium+ Small-				
Inferior Parietal Lobule	R	40	54	-28	25	2350	-4.968945
Postcentral Gyrus	L	3	-43	-25	61	2328	-4.989397
Insula	L	13	-45	-7	13	2755	-6.183497
Postcentral Gyrus	L	40	-51	-25	22	7996	-6.08046
Cuneus	L	18	-24	-91	-2	69011	9.050596
Middle Frontal Gyrus	R	6	27	-7	49	1364	5.579226

Peak Voxel	Side	BA	Talairach Coordinate			NOV	*t*
			x	y	z		
			Large+ Small-				
Inferior Parietal Lobule	R	40	51	-28	25	1485	-4.456243
Precentral Gyrus	L	6	-48	-4	10	2508	-5.742199
Inferior Parietal Lobule	L	40	-66	-31	29	7073	-6.400276
Precuneus	L	7	-24	-67	28	104500	10.28237
Middle Frontal Gyrus	R	6	27	-4	52	3631	6.607982
Cingulate Gyrus	L	32	-6	14	43	2362	5.784618
Middle Frontal Gyrus	L	9	-42	14	31	1728	5.4002

Peak Voxel	Side	BA	Talairach Coordinate			NOV	*t*
			x	y	z		
			Large+ Medium-				
Angular Gyrus	R	39	48	-61	34	2382	5.089946
Angular Gyrus	L	39	-39	-55	34	717	4.511892

5. Discussion and Conclusion

With these contrasts created for both varying rewards and delays, we can address our earlier hypotheses. First, using both the reward and delay contrasts, we must determine if some of the activation we observe matches areas of the brain commonly thought to be involved when making intertemporal choices. This will help us to validate that even with novel stimuli, we are still seeing similar network activity as previous studies. Next, we will switch our focus to the contrasts looking at changes in the delay period. In these contrasts, we will be looking for activation that either supports or opposes our novel tri-phasic delay discounting hypothesis. Last, the contrasts made on the basis of differing monetary rewards will be used to evaluate if different neural activation is elicited by changes in reward value.

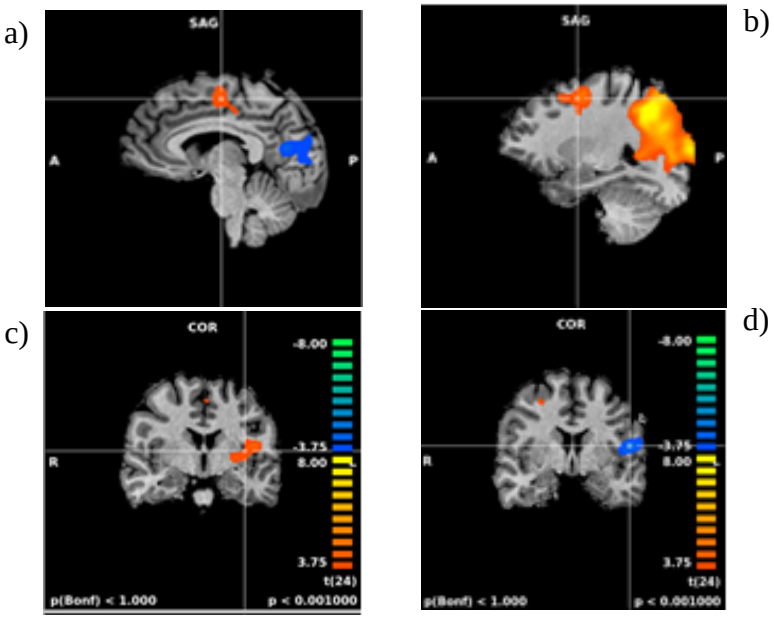


Figure 4. a) Long(o) Short(b) Crosshairs on medial frontal gyrus activation. b) Large(o) Small(b) Crosshairs on middle frontal gyrus activation (c) Long(o) Short(b) Crosshairs on insular activation d) Medium(o) Short(b) Crosshairs on insular activation Note: o – orange b – blue

To examine differences between LL and SS choices, we contrasted both medium and large rewards to small rewards. In addition, we also contrasted both intermediate and long delays to short delays. Similar to previous studies, we observed dorsolateral prefrontal cortex activation for longer delays and larger rewards. This activation is seen in the middle frontal gyrus for larger rewards and the medial frontal gyrus for longer delays (See Figure 4). This activity, while in different regions depending on the variable, further supports the role of prefrontal regions in the brain being responsible for delaying gratification. Additionally, insular activation was found in the long and intermediate delay periods that were contrasted with short delays. Insular regions are considered to be important components of the decision making network as they integrate sensation to emotional states, which eventually leads to action selection (Craig, 2002). Previous models have hypothesized that different parts of the insula are activated in short-term and long-term reward prediction (Tanaka et al., 2016). Supporting this finding, insular activation was also found in our study when participants were making small reward decisions vs large ones. Other delay discounting studies have observed ventral medial prefrontal activation in response to choosing SS rewards; however, no significant activation in this region was observed in our contrasts. The lack of this activity could be a result of slight variations in our delay discounting task compared to other studies or could be caused by participants not receiving immediate reinforcing stimuli while making these decisions. Instead, participants only obtained compensation at the completion of the study. Research has been conducted to evaluate if hypothetical delay discounting tasks generate different results from the real world and their findings suggest that only

slight (Lane et al., 2003) differences are detectable, if any (Madden et al., 2003; Madden et al., 2004). While this factor may have a slight impact on brain activation in delay discounting tasks, the present study would be unable to be conducted without using a slightly hypothetical framework. Also, our study can be compared with other works that have similarly found little activation for SS choices in hypothetical discounting tasks (Wittmann et al., 2007).

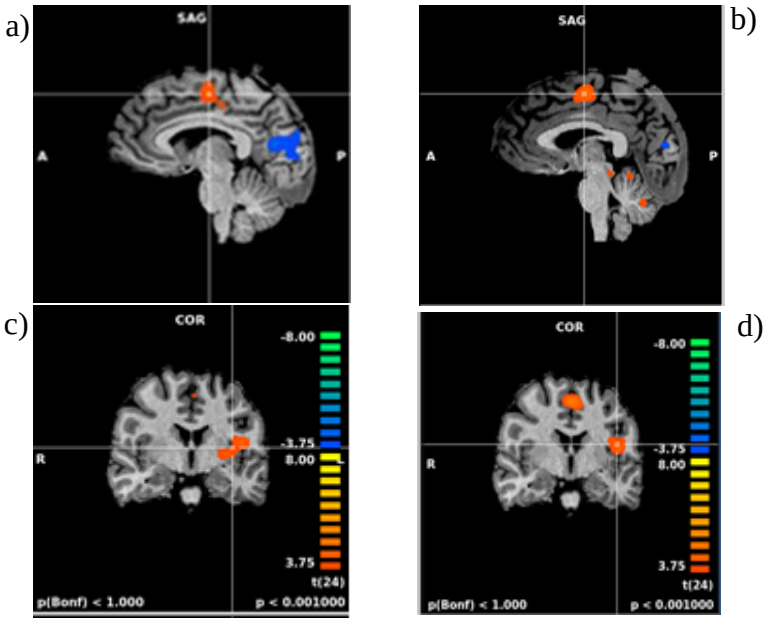


Figure 5. a) Long(o) Short(b) Crosshairs on medial frontal gyrus activation. b) Intermediate(o) Short(b) Crosshairs on medial frontal gyrus activation (c) Long(o) Short(b) Crosshairs on insular activation d) Medium(o) Short(b) Crosshairs on insular activation Note: o – orange b – blue

Taking a closer look at our contrasts involving different delays, we observe common activation for the long and intermediate delay periods in the medial frontal gyrus of the left hemisphere (See Figure 5). This area stands out as significant due to reports of the medial frontal gyrus being involved with delayed choices (MacKillop et al., 2012). This finding, common to both long and intermediate delay periods, suggests that

the medial frontal gyrus is involved in some way in delaying gratification. A different area of the prefrontal cortex is active in our contrasts involving changing reward magnitudes; therefore, this region may also be specific to differentiating between immediate and long-term delays (See Figures 5 and 6). Insular activation is also observed in both the intermediate and long delay periods (See Figure 5). As mentioned previously, the insula is often associated to play a part in delaying gratification and seeing that area active in both of the longer delay periods supports this fact. Common to both of the longer delays was activation in the culmen and precentral gyrus. It is possible that these areas are a part of the neuronal circuit that differentiates between delay periods when it comes to making intertemporal choices, but it is difficult to make any concrete conclusions here with a lack of previous research. These areas are just as likely to be active as a result of visual, auditory, or motor stimuli involved with the task. The neural congruence in activation observed during both the intermediate and long delay periods suggests that our tri-phasic hypothesis of brain activation is likely incorrect. While there are slight differences in activation between the two time periods in the occipital gyrus, temporal gyrus, and fusiform gyrus, these are areas that lack convincing evidence when it comes to playing a part in intertemporal choices. Activation in separate areas of the prefrontal cortex or orbitofrontal cortex would be more likely if a different mechanism was involved in differentiating between intermediate and long time periods. The cuneus is the only area of activation observed for immediate rewards. The areas of the cuneus that were shown to be active lead us to believe that this activation is a result of stimulus saliency. This activation could mean that rewards in the short-term stand out to participants.

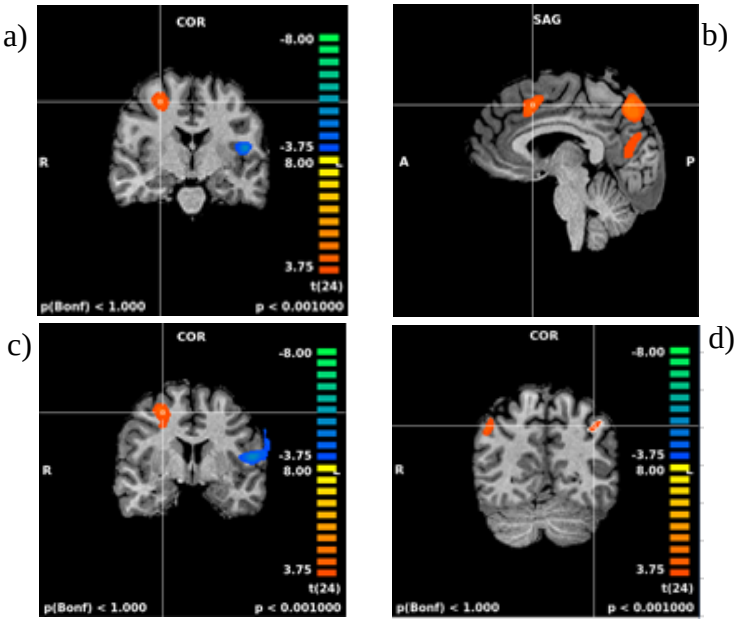


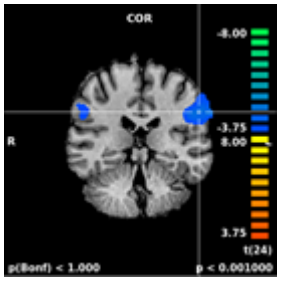
Figure 6. a) Medium(o) Small(b) Crosshairs on middle frontal gyrus activation. b) Large(o) Small(b) Crosshairs on cingulate gyrus activation (c) Large(o) Small(b) Crosshairs on right middle frontal gyrus activation d) Large(o) Medium(b) Two clusters seen are left and right angular gyrus activation Note: o – orange b – blue

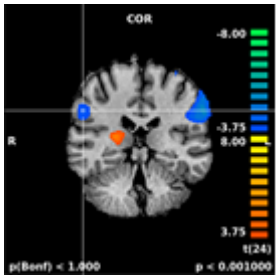
The middle frontal gyrus was a common area of activation for both medium and large rewards and increasing the magnitude of the reward also increased activation in this region (See Figure 6). With prefrontal regions being commonly found in delay discounting studies, this area likely plays a key role in choosing larger rewards. Specific middle frontal gyrus activation has also been seen in similar discounting studies dealing with monetary rewards (Xu et al., 2009). During presentation of medium rewards, only the left middle frontal gyrus was active (See Figure 6). When the magnitude of the reward grew, this activation also included the recruitment of the right middle frontal gyrus. Bilateral recruitment has been discussed as a way for the prefrontal cortex to cope with more cognitive challenges (Höller-Wallscheid et al., 2017). It would make sense that a larger monetary reward would be perceived by the brain to be a more difficult

decision and result in the bilateral activation observed as the value of the reward increases. Large reward magnitudes also elicited activation in the cingulate gyrus. As hypothesized from previous studies, the cingulate gyrus has shown its influence when choosing larger rewards no matter the time period (Wittmann et al., 2007). With the absence of cingulate gyrus activation when varying the delay period, these results support the assumption that the cingulate gyrus is involved in decisions and expectancies for larger rewards across all time periods. Precuneus and cuneus activation was seen for larger reward values and the area of activation in this region increased with increasing reward value. While these results may seem contradictory to our assumption of stimulus saliency made in response to cuneus activation during short delay periods, the way our contrasts are created would still support this theory. As an immediate reward may draw more attention to itself, so might a reward that is higher in magnitude, thus eliciting such a large group of activation that increased with reward value. The direct contrast between intermediate and large reward values showed only bilateral activation of the angular gyrus (See Figure 6). Neuroimaging studies have provided evidence that the angular gyrus is commonly active when individuals are making mathematical calculations. With the rewards of our study being monetary in nature and the difference in value between large and medium rewards being upwards of 495,000, angular gyrus activity is likely a result of increased mental math when participants answer questions involving large rewards.

Still looking at our contrasts involving differing reward value, but switching gears to look at the smaller rewards, common activation is seen in the inferior parietal lobule (See Figure 7). The inferior parietal lobule has been reported to take part in executive

function, inhibitory control, (Hedden & Gabrieli, 2010) and has been found active when subjects make more difficult delay discounting choices (McClure et al., 2004; Monterosso et al., 2007). Our findings do not seem to fit well with these conclusions; however, the inferior parietal lobule is also involved in the attention network (Ptak, 2012). Decisions in the short term may make individuals feel like they must be more attentive, which may explain the observed activation in this region. Precentral and postcentral gyrus activation was also found for small rewards values. Further research that specifically looks at how the magnitude of a reward may alter brain activation is required to say anything conclusive in regard to these areas.

a) 



b)

Figure 7. a) Large(o) Small(b) Two activation clusters represent bilateral activation of the inferior parietal lobule. b) Medium(o) Small(b) Crosshairs on right inferior parietal lobule activation Note: o – orange b – blue

To expand this study, future research could look at how brain activation patterns may change for individuals considered to be impulsive. Impulsive individuals have been observed to have altered brain activity when it comes to making intertemporal choices (Stoeckel et al., 2013). These changes are often observed as insufficient functioning of executive control regions such as the prefrontal cortex. If clear evidence was found that one such brain region elicited significantly different activation only seen in impulsive participants, fMRI could be used to determine one's propensity to forming addictions.

In summary, this article aimed to clarify the differences in brain activation that may result from participant perceptions of a delay period or reward value. Additionally, we proposed that a tri-phasic delay discounting hypothesis would better explain behavioral responses to typical delay discounting questions involving exceedingly long delays, and that these excessive delays would call on separate neuronal networks. Our findings did not provide any evidence to support this tri-phasic hypothesis. When the delay to a reward was increased, common activation in the medial frontal gyrus, precentral gyrus, and insula was found. Varying the value of a reward did result in slight variations in brain activation, with the cingulate gyrus notably being active when choosing the largest of rewards. Additionally, the middle frontal gyrus increased in activation and even displayed bilateral recruitment with increasing reward value. Showing that similar networks in the brain seem to be responsible for all delays, even those into the far future, may aid researchers in determining the best function to properly model behavioral responses to intertemporal choices. Moreover, when these results are combined, they provide strong evidence that the value and delay of a reward are handled by dissociable neural networks when making intertemporal choices.

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