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# Emotional arousal predicts intertemporal choice

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## Abstract

People generally prefer immediate rewards to rewards received after a delay, often even when the delayed reward is larger. This phenomenon is known as temporal discounting. It has been suggested that preferences for immediate rewards may be due to their being more concrete than delayed rewards. This concreteness may evoke an enhanced emotional response. Indeed, manipulating the representation of a future reward to make it more concrete has been shown to heighten the reward's subjective emotional intensity, making people more likely to choose it. Here we use an objective measure of arousal – pupil dilation – to investigate if emotional arousal mediates the influence of delayed reward concreteness on choice. We recorded pupil dilation responses while participants made choices between immediate and delayed rewards. We manipulated concreteness through time interval framing: delayed rewards were presented either with the date on which they would be received (e.g., "$30, May 3"; DATE condition, more concrete) or in terms of delay to receipt (e.g., "$30, 7 days; DAYS condition, less concrete). Contrary to prior work, participants were not overall more patient in the DATE condition. However, there was individual variability in response to time framing, and this variability was predicted by differences in pupil dilation between conditions. Emotional arousal increased as the subjective value of delayed rewards increased, and predicted choice of the delayed reward on each trial. This study advances our understanding of the role of emotion in temporal discounting.

### Keywords

Emotion; pupil dilation; arousal; intertemporal choice; temporal discounting

Many of our everyday choices involve weighing the benefits of smaller rewards now against larger rewards in the future. These choices are known as *intertemporal* decisions (Strotz, 1956; Laibson, 1997). For example, we may have to choose whether to spend our paychecks now or to save money for retirement. People vary widely in the degree to which they discount the value of future rewards (Peters & Buchel, 2011), and excessive *temporal discounting* underlies many societal problems, including obesity (Jarmolowicz et al., 2014) and addiction (MacKillop et al., 2011; Reynolds, 2006; Madden & Bickel, 2010). Despite this variability, many people prefer immediate rewards to rewards received after a delay, even when the delayed reward is larger (Strotz, 1956).

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One potential explanation for the widespread inclination toward immediate rewards is that they may evoke a greater emotional response than delayed rewards do. This is a dominant theory in the intertemporal choice literature, and it has been formalized in two-systems models, which posit that our preference for immediate rewards stems from “hot” emotional responses, while patience emerges from more deliberative, “cold” reasoning (Figner, Mackinley, Wilkening, & Weber, 2009; McClure, Laibson, Loewenstein, & Cohen, 2004; Laibson, 1997). Despite these claims, few studies have measured emotion during these decisions.

Emotion is a multidimensional construct, comprised of components including subjective feelings, physiological response, motor expression, action tendency, and evaluation or appraisal (Scherer, 2000, 2005). Thus, to gain a nuanced understanding of how emotion relates to decision-making, we should attempt to link specific affective variables to specific decision variables (Phelps, Lempert & Sokol-Hessner, 2014). One important component of emotion is physiological arousal. Although arousal is limited in its specificity, it is an objective measure of emotion, and it does not depend on an explicit evaluation of one’s emotional state. In a recent study, we measured arousal using pupil dilation while people made intertemporal choices (Lempert, Glimcher, & Phelps, 2015). We found that arousal did not reliably correlate with the subjective value of either immediate or delayed rewards. Rather, this relationship varied depending on the structure of the choice set. Greater arousal responses were observed when rewards were better than expected, and not when they were worse than expected, whether those rewards were immediate or delayed. Thus, this was not just an arousal response, but a positively-valenced arousal response, consistent with the interpretation that we captured an emotional response, and not simply a reaction to novelty or surprise. This finding is at odds with models suggesting that it is the emotional response to the immediate option that drives temporal discounting. Instead, it shows that arousal, one principal component of emotion, during this decision process is flexible and context-dependent.

Given this flexibility, another potential way to alter arousal during intertemporal choice might be to change the framing of delayed rewards, to make them more concrete. Immediate rewards are typically construed as more concrete relative to delayed rewards. According to the construal level theory (CLT) framework (Trope & Liberman, 2003), time modulates the representation of events so that more temporally distal events seem more abstract, and more proximal events seem more concrete, and this can influence preferences (Trope & Liberman, 2000). In support of this, when delayed rewards are framed as more concrete (e.g., when a context is specified in which a future reward amount can be used), then individuals tend to become more patient (Benoit, Gilbert, & Burgess, 2011; Peters & Buchel, 2010; Daniel, Stanton, & Epstein, 2013; Palombo, Keane, & Varfaellie, 2014), and they tend to rate more concrete delayed rewards as higher in subjective emotional intensity (Benoit et al., 2011). Moreover, individuals who can more vividly imagine the future tend to become more patient after considering concrete future rewards (Peters & Buchel, 2010). It has been suggested that emotion mediates the link between future reward concreteness and patience (Liu, Feng, Chen, & Li, 2013; Lebreton et al., 2013), but to date, these studies have relied almost exclusively on subjective ratings of emotion. Here we use an additional measure of emotion, an objective measure of physiological arousal, to investigate the hypothesis that increased emotional arousal to more concrete delayed rewards leads to more patient choice.

In our study, we measured arousal using pupil dilation while participants performed an intertemporal choice task. Pupil dilation is a reliable measure of sympathetic nervous system activity in response to emotional stimuli (Bradley, Miccoli, Escrig, & Lang, 2008). We performed a simple manipulation of concreteness, in which the delayed rewards in our task were framed either in terms of the date on which the rewards would be received (DATE condition; e.g., $30 on September 6) or the number of days that an individual had to wait to receive the reward (DAYS condition; e.g., $30 in 30 days). This manipulation was inspired by a series of studies (Read, Frederick, Orsel, & Rahman, 2004; LeBoeuf, 2006; DeHart & Odum, 2015) that showed that people were more patient when delayed rewards were framed in terms of the date on which they would be received. Although the psychological mechanism behind this "date/delay effect" is unclear (Read et al., 2004; DeHart & Odum, 2015), one possibility is that people can more concretely imagine spending money on future dates, rather than after particular time intervals. Therefore, we hypothesized that individuals would show greater emotional arousal to delayed rewards in the DATE condition, and that they would be more patient in this condition, relative to the DAYS condition.

## Method

### Intertemporal choice task

Participants performed an intertemporal choice task while pupillometric data were collected. On each trial, participants were first presented with a 1-second fixation cross, followed by a screen that showed a monetary reward available today (either "$10 today" or "$20 today") for 4 seconds. Following this, a monetary reward of larger magnitude available after one of the delays [7 days, 30 days, 60 days, 100 days, 180 days] was displayed for 4 seconds. Delayed reward magnitudes depended on the magnitude of the immediate reward. That is, $10 today was presented with $11, $15, $20 and $30 after a delay, and $20 today was paired with $22, $30, $40 and $60 after a delay. In order to probe for variability in discount rates, each delayed reward magnitude was paired with each delay.

On half of the trials, the delayed reward was presented in terms of the date on which the reward would be received (e.g., "$20 May 19"; DATE condition), and on the other half, the reward was presented with the number of days that the participant would have to wait to receive it (e.g., "$20 30 days"; DAYS condition). Then, participants saw the word "Choice?" appear on the screen for 3 seconds. While they viewed this screen, they pressed either "1" or "2" to indicate whether they preferred the first (immediate) or second (delayed) reward option. After the allotted 3 seconds, a fixation point appeared for 2.5 seconds, followed by an outcome screen (3 seconds), which showed the participants what they had just chosen. After a 5 second inter-trial interval, the next trial began. There were forty distinct choices, each presented in both the DAYS and the DATE condition, yielding eighty trials total (see Figure 1 for trial layout). The presentation order of trial types was random. The paradigm was programmed using E-Prime 2.0 Stimulus Presentation Software (Psychology Software Tools, Sharpsburg, PA).

Our previous research showed that pupil dilation responses are more responsive to delayed reward values when delayed rewards are more variable in the task, whereas pupil dilation responses are more sensitive to immediate reward values when immediate rewards are more variable (Lempert et al., 2015a). Since we specifically sought to isolate the arousal response to the delayed reward option, we constructed the choice environment so that delayed rewards were more variable. We also presented options sequentially in order to capture arousal responses to the immediate and delayed reward options separately.

To increase the saliency and relevance of their choices and to render our experiment incentive-compatible, participants were told at the outset that one of their responses would be randomly selected and that they would receive the amount they chose on that trial, at the delay specified. They were informed that if they chose the immediate reward on the randomly selected trial, they would receive the money in cash as additional compensation after the session; conversely, if they chose the delayed reward, they would receive the money in their personal checking account via Paypal (www.paypal.com) after the delay had elapsed. This method of payment was used to obviate the transaction cost associated with returning to the laboratory after the delay had elapsed.

## Pupil diameter data collection

To collect pupil dilation data, we used Eye Link 1000 eye tracking equipment (SR Research, Ontario, Canada). We sampled pupil diameter at 250 Hz throughout the entire task. Subjects were seated 55 cm from the computer screen (screen size: 36.5 x 27.5 cm; 1028 x 768 pixels), with their chins on a chinrest. They were asked to minimize blinking and to focus their eyes on the center of the screen throughout the experiment. Trials were divided into four blocks. Participants were allowed to take a break between blocks, and the eye tracker was re-calibrated between blocks.

## Analyses

**Choice data analysis—**To quantify each individual's temporal discounting rate, we fit his or her choices to the hyperbolic model of temporal discounting (Mazur, 1987; Green & Myerson, 2004; Kable & Glimcher, 2007) separately for the DATE and DAYS conditions and used maximum likelihood estimation to determine the best-fitting discount rate parameter $k$:

$$\mathrm{SV}_{\mathrm{del}}=\mathrm{A}/(1+k\mathrm{D}) \quad \text{(Equation 1)}$$

In this equation, $\mathrm{SV}_{\mathrm{del}}$ is the subjective value of the delayed reward, A is the amount of the delayed reward, D is the delay, and $k$ is the parameter that represents the participant's discount rate (higher $k$ values correspond to more impatience).

In order to ensure that the hyperbolic model adequately fit our data, we also fit the data in each condition separately, and for both conditions together, with the exponential model (Samuelson, 1937):

$$\mathrm{SV}_{\mathrm{del}} = \mathrm{A}e^{-k\mathrm{D}} \quad \text{(Equation 2)}$$

Here the parameters are the same as in the hyperbolic model, and *e* is a mathematical constant (base of the natural logarithm).

We used the *k* discount rate parameter from the better-fitting model to calculate the subjective value of the delayed reward for every trial for every participant (Kable & Glimcher, 2007). Since our primary comparisons were performed within-subjects, we assumed a linear utility function (see Kable & Glimcher, 2007; Andreoni & Sprenger, 2012 for implications of this assumption). To compare discount rates between conditions, we conducted a paired t-test on the log-transformed *k*-parameters.

**Pupil pre-processing—**Eye-blinks were categorized as pupil dilation changes that transpired too quickly to represent actual pupil dilation; they were removed using linear interpolation. We baseline-corrected the pupil data, by dividing each pupil diameter measurement by the average pupil diameter over 1 second prior to each trial (as in Henckens, Hermans, Pu, Joels, & Fernandez, 2009).

**Pupil general linear model analysis—**In order to investigate potential value-related activity in the pupil diameter data (Value Model), we constructed a general linear model (GLM), which consisted of the following predictors (as individual 1s in a series of 0s): a sustained component (boxcar) during the period that the immediate reward was presented and a sustained component during the period that the delayed reward was presented. In addition, we included each of these regressors in the model parametrically modulated by: 1) presentation condition (whether it was a DATE or DAYS trial; DATE = 1, DAYS = −1), 2) relative value equivalence (RVE; the negative absolute difference between the value of the immediate reward and the subjective value of the delayed reward on that trial; when this is higher, the trial is more difficult) and 3) the subjective value (the immediate reward boxcar was modulated by the immediate reward value, $10 or $20, and the delayed reward boxcar regressor was modulated by the subjective value of the delayed reward on that trial). Therefore, our final Value Model contained eight predictors: the immediate and delayed reward boxcars, the immediate and delayed reward boxcars modulated by presentation condition (DATE/DAYS), the immediate and delayed reward boxcars modulated by RVE, and the boxcars modulated by subjective value. Each regressor was then convolved with a canonical pupil response function (described in de Gee, Knapen & Donner, 2014; Lempert, Chen & Fleming, 2015):

$$\mathrm{h(t)} = s * \mathrm{t}^{\mathrm{w}} e^{(-\mathrm{t}*\mathrm{w}/\mathrm{t}_{\mathrm{max}})},$$

where w is the width and $t_{max}$ is the time-to-peak (in milliseconds) of the impulse response function. We used canonical values for these two parameters (see de Gee et al., 2014; Hoeks & Levelt, 1993): w = 10.1; $t_{max}$ = 930 ms. We scaled the function by a factor $s = 1/10^{27}$ (as in Wierda, van Rijn, Taatgen, & Martens, 2012), and resampled the predicted response to match the sample rate of the data (250 Hz). The convolved regressors were horizontally concatenated into a design matrix.

A complementary model examined the relationship between pupil dilation and choice of immediate or delayed reward on any given trial (Choice Model). Because choice is collinear with the subjective value and RVE regressors, the choice model contained only six regressors: the immediate and delayed reward boxcars, the boxcar regressors modulated by presentation condition (DATE: 1, DAYS: −1), and the boxcar regressors modulated by choice (delayed reward chosen: 1, immediate reward chosen: −1).

For both the Value Model and the Choice Model, multiple regression yielded the best-fitting beta weights for each regressor, separately for each subject. Statistical inference at the population level was carried out by comparing these values to the null hypothesis that the average beta weight is zero, using one-sample t-tests. Beta weights not significantly different from zero are indicative of no significant effect of our task variables (i.e., DATE/DAYS, subjective value, and RVE in the Value Model and DATE/DAYS and choice in the Choice Model) on pupil dilation data.

**Control for eye movements—**It has recently been demonstrated that gaze direction and eye movements may produce systematic errors in pupil diameter measurements (Brisson et al., 2013). To control for potential eye movement artifacts, we instructed participants to fixate on the center of the screen during the entire measurement period. In addition, we re-calibrated the eye tracker at the beginning of each block, and we used a gaze-contingent display at the start of each block to ensure that the fixation point did not change in between blocks. Nevertheless, participants did make some minor eye movements. In order to ensure that these eye movements were not influencing our effects, we calculated a “deviation index” for each trial for each subject (as in Lempert et al., 2015b). First, we calculated the Euclidean distance of the eye from the fixation point for each recorded pupil diameter sample. Then, we normalized these distances by dividing each by the median (the median was used as the measure of central tendency due to the skewed nature of these distributions). Finally, we averaged these values in order to determine a “deviation index” for each trial. In addition, we calculated the variance of these values to determine the eye movement variance on each trial, which might also influence pupil dilation. We constructed four additional general linear models: two in which each of the temporal regressors was parametrically modulated by the deviation index on that trial (thereby adding an additional two regressors to our Value Model and our Choice Model), and two in which each of the temporal regressors was parametrically modulated by the eye movement variance on that trial.

**Control for luminance—**In addition to indexing arousal, pupil diameter is strongly modulated by stimulus luminance. By including the onset of the immediate and delayed reward stimuli in our model, we were able to control for luminance changes that occurred when a new stimulus appeared on the screen. We also attempted to keep luminance across trials approximately constant. The delayed reward magnitude was always a two-digit number, and on DATE trials, the month was always abbreviated to either 3 or 4 letters. Moreover, since the actual dates presented were random between subjects, there would be no correlation between luminance on DATE trials and any variable of interest (e.g., subjective value). On the DAYS trials, however, the number of days varied from being presented with 1 digit (as in “7 days”) to 3 digits (as in “180 days”), so there is a correlation between delay and mean luminance. Therefore, we conducted an additional analysis to control for luminance differences among these trials. We calculated the mean relative brightness of each delayed reward stimulus using ImageJ software (35 stimuli total; range: 46.63 – 53.04) to obtain a “luminance index” that we could use as a parametric modulator for each trial in the DAYS condition. For the DATE condition, we set the luminance index equal to the average brightness across stimuli in the DAYS condition (49.8). To ensure that our results were not luminance-driven, we constructed new models in which we added this luminance index regressor to our Value and Choice models described above (Note: we removed the DATE/DAYS predictor for this control analysis since it is collinear with luminance index).

# Results

## Participants

Sixty participants completed the study (mean age = 23.43; *SD* = 7.7; 26 M, 34 F; 13 Asian, 9 Black, 9 Hispanic, 24 Caucasian, 5 Mixed Race). Nine were excluded because their data could not be fit to the hyperbolic model (n = 4)[1] or they produced unreliable eye tracking data (n = 3) or due to technical errors that resulted in lost data (n = 2), so analyses were performed on data from 51 participants (mean age = 23.02; *SD* = 7.6; 22 M, 29 F; 11 Asian, 8 Black, 7 Hispanic, 21 Caucasian, 4 Mixed Race). Participants were recruited via posted advertisement on the New York University campus, and were primarily New York University students. Approval was obtained from the University Committee on Activities Involving Human Subjects at New York University, and all participants signed a consent form before the experiment.

## Behavioral results

We fit the hyperbolic (Equation 1) and exponential (Equation 2) models for each subject, for each condition (DATE and DAYS) separately, and also for the two conditions combined. Taking the median across subjects, in the DATE condition, the hyperbolic model (median $k$: 0.013; $R^2 = 0.633$; AIC = 23.55) was a slightly better fit than the exponential model (median $k$: 0.008; $R^2 = 0.629$; AIC = 23.56). The same was true for the overall dataset (hyperbolic median $k$: 0.014; $R^2 = 0.624$; AIC = 45.73; exponential median $k$: 0.009; $R^2 = 0.598$; AIC = 47.19). In the DAYS condition, the exponential model had a small advantage (hyperbolic median $k$: 0.015; $R^2 = 0.651$; AIC = 22.57; exponential median $k$: 0.01; $R^2 = 0.667$; AIC = 22.02). Nevertheless, 32/51 subjects were better fit by the hyperbolic model in the DATE condition, 29/51 subjects were better fit by the hyperbolic model in the DAYS condition, and 37/51 subjects were better fit by the hyperbolic model when considering the full dataset, so we decided to use the $k$ parameters derived from the hyperbolic model for all further analyses.

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[1] Of these four subjects, one chose all delayed rewards, two showed inconsistent preferences (i.e., switching back and forth between choosing immediate and delayed rewards as delayed rewards increased in magnitude), and one had too many missed trials for a discount rate to be computed.

The mean discount rate parameter $k$ for participants in the DATE condition was 0.024 ($SD$ = 0.039; range: 0.002 – 0.22). In the DAYS condition, the mean discount rate was also 0.024 ($SD$ = 0.04; range: 0.003 – 0.28). Because discount rates are not normally distributed, we log-transformed them before performing statistical tests. A paired $t$-test showed that, in contrast to prior work, there were no overall differences in discount rate between the DATE and DAYS conditions in our sample ($t_{50} = 0.44$; $p = 0.66$).

Although on average the discount rates did not differ between conditions, there was variability among individuals. Twenty-seven of 51 subjects had lower discount rates in the DATE condition, while the remaining 24 had lower discount rates in the DAYS condition (Figure 2). We performed likelihood ratio tests on the discount rate $k$ parameters to identify individuals with differences in parameters between the conditions stronger than a cutoff value of $p = 0.05$ (as in Sokol-Hessner et al., 2009). Specifically, the likelihood ratio test for each subject compared a model with a single discount rate across conditions to a model with one discount rate per condition. Sixteen of 51 subjects showed significant differences in discount rate between the DATE and DAYS conditions. Of these, 10 were more patient in the DATE condition, and 6 were significantly more patient in the DAYS condition. Therefore, participants did make different choices in the two conditions, but a subset seemed to favor the DAYS framing, and another subset favored the DATE framing.

We reasoned that the discrepancy between our results and the results of previous studies (e.g., LeBoeuf, 2006; DeHart & Odum, 2015; Read et al., 2004) could be due to the fact that some of the delays used in the current study were shorter than those used in prior studies. For example, LeBoeuf (2006) found that the date/delay effect did not emerge unless the delay was 2 months or more, and in general, the effect of interval description weakens as time intervals decrease. This may be due to the fact that people tend to use date descriptors in their language as the time interval increases (Golding, Magliano & Baggett, 1995), and they use interval descriptors otherwise. Therefore, a time may seem closer when it is described in a way that is consistent with the way that an individual would describe it. It is possible that, for short time intervals, the date/delay effect goes away or even reverses.

2To investigate this in our dataset, we examined the proportion of delayed rewards chosen at each delay for each participant, in both the DATE and DAYS conditions.[2] We conducted paired $t$-tests and estimated Cohen's $d$ for each delay. We found a trend toward a positive relationship, wherein the longer the delay, the larger the effect size (i.e., the more likely the participant was to choose a delayed reward in the DATE condition than in the DAYS condition; $r = 0.74$; $p = 0.16$; N = 5). When collapsing across the two longest delays (100 and 180 days), participants were significantly more patient in the DATE relative to the DAYS condition ($t_{50} = 2.26$; $p = 0.03$; effect size = 0.3; Cohen's $d = 0.64$). When collapsing across the two shortest delays (7 days and 30 days), there was no difference in discount rate between the two conditions ($t_{50} = 0.78$; $p = 0.44$). This provides some evidence that the date/delay effect that has been reported in the literature may only exist for long time intervals.

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[2] Fitting and comparing discount rates for each delay was not appropriate because of the small number of trials for each delay in each condition.

### Emotional arousal results

In order to examine which task variables could explain our pupil dilation data, we constructed two general linear models. In the Value Model, we modeled the presentation of the immediate reward and delayed reward as boxcar regressors, and then parametrically modulated them by presentation condition (i.e., the DATE/DAYS dummy regressor), RVE (relative value equivalence: the negative absolute difference in subjective values between the immediate and delayed rewards), and subjective value (the immediate reward boxcar was modulated by the immediate reward value, and the delayed reward boxcar was modulated by the subjective value of the delayed reward, determined using participants' discount rates and the hyperbolic model)[3]. Average beta weights for each of our eight predictors are shown in Table 1. First, we found a significant negative main effect of immediate reward presentation ($t_{50} = -4.15$; $p = 0.0001$; effect size = 0.5; Cohen's $d = 1.17$) and delayed reward presentation ($t_{50} = -2.08$; $p = 0.04$; effect size = 0.28; Cohen's $d = 0.59$). This is consistent with the fact that the onset of novel visual stimuli will produce a change in luminance, which will result in pupil constriction. By including the main effect regressors in our model, we control for any pupil diameter changes that would be due to visual stimulation alone.

During the presentation of the immediate reward, there were no significant effects of immediate reward value ($t_{50} = -0.79$; $p = 0.41$), RVE ($t_{50} = 1.38$; $p = 0.18$) or the DATE/DAYS manipulation ($t_{50} = 0.58$; $p = 0.59$) on pupil dilation.

During presentation of the delayed reward, pupil dilation was significantly predicted by RVE ($t_{50} = 3.06$; $p = 0.004$; effect size = 0.4; Cohen's $d = 0.87$; Figure 3a). Since RVE is a proxy for difficulty, pupil dilation was larger when choices were more difficult. This is consistent with previous literature, implicating pupil dilation as a measure of arousal due to cognitive load and difficulty (e.g., Kahneman & Beatty, 1966). Notably, however, pupil dilation increased with the subjective value of the delayed reward, even when controlling for RVE ($t_{50} = 3.69$; $p < 0.001$; effect size = 0.46; Cohen's $d = 1.04$; Figure 3a). There was no effect of the DATE/DAYS manipulation on pupil dilation during the delayed reward presentation ($t_{50} = 0.34$; $p = 0.74$). The effects of RVE and value remained when controlling for eye movements, as defined by the deviation index (RVE: $t_{50} = 3.01$; $p = 0.004$; effect size = 0.39; Cohen's $d = 0.85$; subjective value: $t_{50} = 3.58$; $p < 0.001$; effect size = 0.45; Cohen's $d = 1.01$; average eye movement = 152.76 pixels (5.47 cm); average eye movement SD = 58.2 pixels; SD across subjects: 75.07 pixels) and variance in eye movements (RVE: $t_{50} = 2.61$; $p = 0.01$; effect size = 0.35; Cohen's $d = 0.74$; subjective value: $t_{50} = 5.05$; $p < 0.001$; effect size = 0.58; Cohen's $d = 1.43$). RVE and subjective value also remained significant when controlling for luminance differences between trials (RVE: $t_{50} = 2.26$; $p = 0.02$; effect size = 0.3; Cohen's $d = 0.64$; subjective value: $t_{50} = 4.76$; $p < 0.001$; effect size = 0.56; Cohen's $d = 1.35$).

In the Choice Model, we included presentation condition (DATE/DAYS) and choice (delayed reward chosen: 1; immediate reward chosen: −1) as parametric modulators.

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[3] For the sixteen participants who showed significant differences in discount rate between the DATE and DAYS conditions according to the likelihood ratio tests, the subjective value of the delayed reward was determined by using a different $k$ parameter for the two conditions. For the remainder of the subjects, one $k$ parameter was used for all trials.

Average beta weights for predictors in this model are shown in Table 2. Again, the DATE/DAYS manipulation did not predict pupil dilation response (at immediate reward presentation: $t_{50} = 0.63$; $p = 0.53$; at delayed reward presentation: $t_{50} = 0.37$; $p = 0.71$). Furthermore, pupil dilation during the immediate reward presentation was unrelated to choice ($t_{50} = 1.37$; $p = 0.18$). Pupil dilation during the delayed reward presentation, however, significantly predicted choice of the delayed reward ($t_{50} = 4.64$; $p < 0.0001$; effect size = 0.55; Cohen's $d = 1.31$; Figure 3b). This effect remained when controlling for eye movements ($t_{50} = 4.65$; $p < 0.\ 0.0001$; effect size = 0.55; Cohen's $d = 1.32$), variance in eye movements ($t_{50} = 4.8$; $p < 0.0001$; effect size = 0.56; Cohen's $d = 1.36$), and luminance differences between trials ($t_{50} = 4.44$; $p < 0.0001$; effect size = 0.53; Cohen's $d = 1.26$).

## Emotional arousal predicts individual differences in response to time interval framing

The null effect on pupil dilation of our DATE/DAYS manipulation is unsurprising given that the manipulation was not effective in systematically changing discount rates. However, there were individual differences in response to the manipulation, with some who were more patient in the DATE condition and some who were more patient in the DAYS condition. Since pupil dilation is closely tied to the subjective value of the delayed reward, we predicted that the difference in discount rate between the two conditions would be related to the difference in pupil dilation response in the two conditions. To perform this analysis, we first averaged the pupil diameter from 1 – 4 seconds following the onset of the delayed reward for every trial, for every participant (the mean pupil dilation response; see Henckens et al., 2009; Lempert et al., 2015a). We then averaged these pupil dilation responses for the DATE and the DAYS conditions separately, and subtracted them, to get a difference in pupil dilation response between the two conditions for each subject. We plotted this difference against the difference in log-transformed discount rate (Figure 4). There was a significant negative correlation between these two variables, indicating that the larger the pupil dilation response in the DATE relative to the DAYS condition, the more patient the participant was in the DATE compared to the DAYS condition ($r = -0.39$; $p < 0.005$), and vice versa.

This correlation has two possible interpretations. This could, of course, be a corollary of our findings about subjective value and choice. That is, if a participant was more likely to choose delayed rewards in the DATE condition relative to the DAYS condition, he or she would exhibit higher arousal in the DATE condition because those rewards were, on average, more valuable. The second interpretation is that there is an effect of condition on arousal over and above the effect of value. To resolve this ambiguity, we plotted the difference in discount rate between conditions for each subject against the DATE/DAYS regression coefficient for each subject from the Value model. Since this coefficient reflects the variance in pupil dilation explained by the condition (DATE/DAYS) over and above the effects of subjective value and RVE, the correlation between this and the difference in discount rate would inform us whether the second interpretation is true. The correlation between these two variables is not significant ($r = 0.05$; $p = 0.70$). Thus, we believe that this result is secondary to our finding that arousal reflects the subjective value of the delayed reward being considered.

## Discussion

In this study, we measured pupil dilation while participants made choices between immediate rewards and delayed rewards framed as either more concrete ("DATE" condition) or more abstract ("DAYS" condition), in order to investigate the role of emotional arousal in preferences for concrete delayed rewards. We found that pupil dilation during the presentation of the delayed reward was directly related to the subjective value of that delayed reward, even when controlling for the relative value equivalence between the choice options (a proxy for difficulty). Furthermore, we showed for the first time that pupil dilation during the presentation of a delayed reward predicts whether a participant will choose to be patient on that particular trial.

We did not find any overall effect of our DATE/DAYS manipulation on the emotional arousal response, nor did we replicate the date/delay effect on choice that was shown in previous studies (Read et al., 2004; LeBoeuf, 2006; DeHart & Odum, 2015). One possibility is that the delays that were used in the current study were shorter than some of the delays used in the previous studies, and the range of delays we used was smaller. It is plausible that there are boundary conditions to the date/delay effect. Since people tend to use interval descriptors when referring to times in the near future (Golding et al., 1995), describing delayed rewards in terms of the date on which they will be received may not be appropriate for rewards in the near future. In our data set, we found a trend indicating that this may be the case – the longer the delay until reward receipt, the smaller the effect size for the difference in discount rate between the DATE and DAYS conditions. There are other procedural differences between our study and previous studies that may explain our failure to replicate the date/delay effect. We presented the options sequentially, rather than simultaneously, with the immediate reward always being presented first. If the date/delay effect emerges from a change in how the immediate reward is processed in the presence of the delayed reward, then this may contribute to the discrepancy. Moreover, the calendar year was not included in our date descriptions, and this may have reduced the concreteness and/or certainty associated with the date condition. We did not include this extra attribute in order to better control visual stimulation between conditions, and we are confident that the calendar year was apparent to participants, since no delay was longer than 6 months. Finally, we used a within-subject design with randomly intermixed trials, while most previous studies used a between-subject design and/or presented the date and delay conditions in separate blocks. Since discount rates are highly susceptible to order presentation (Robles & Vargas, 2008; Lempert et al., 2015a), these factors may have led to our inability to replicate this effect as well.

This null behavioral finding suggests that either the date framing does not alter the concreteness of the delayed reward, or that increased concreteness does not lead to reduced temporal discounting. Since there is a body of research linking delayed reward concreteness to increased patience (Benoit et al., 2011; Peters & Buchel, 2010), we favor the former explanation. Insofar as the date/delay manipulation is effective, it might be because date framing changes perceived similarity between rewards, leads to differential time estimation, or leads to differences in attention to attributes, just to name a few alternative hypotheses (see Read et al., 2004 for discussion).

Although the date/delay manipulation was not consistently effective in our study, we were nevertheless able to take advantage of the between-subject variability to examine how emotional arousal could explain differences in the response to the manipulation. In line with the finding that emotional arousal increases with the subjective value of the delayed reward, emotional arousal differences between the DATE and DAYS conditions predicted whether participants were more patient in one condition or the other. This effect was driven by the differences in delayed reward subjective value in the two conditions, and could not be attributed to differences in response to the framing manipulation, independent of value. To our knowledge, this is the first evidence of arousal tracking the effectiveness of a temporal discounting manipulation.

In the current study, we did not observe any relationship between value and the immediate reward presentation, nor did emotional arousal during the presentation of the immediate reward predict choices. Importantly, however, we have previously shown that the more variable reward in the paradigm (in this case, the delayed reward) will elicit an emotional arousal response correlated with its value (Lempert et al., 2015a). For this reason, we expected that the delayed reward would elicit more emotional arousal in this experiment. We nonetheless probed the relationship between pupil dilation and value during both immediate and delayed reward presentation. Since we expected a null effect given our design and previous research, we make no claims about the emotional response to the immediate reward and its relationship to choice. Our results provide further evidence that emotional arousal is context-dependent and likely plays a modulatory role in value computation (Phelps et al., 2014).

The finding that arousal increased with the subjective value of the delayed reward and that this relationship remained significant when controlling for RVE, is consistent with our previous research (Lempert et al., 2015a). Two novel findings of the current study, however, are: 1) RVE (i.e., choice difficulty) is a significant predictor of pupil dilation, and 2) pupil dilation predicted choice of the delayed reward. We believe that we did not find these effects in our previous study because of methodological differences between the two studies. First, in the current study, we presented options sequentially; thus, the processing of the delayed reward was unconfounded by simultaneous processing of the immediate reward. Secondly, we used a different analysis technique in the current study. In the previous study, we took an average across a 3-second window as our index of pupil dilation. Here, we used a GLM approach analogous to the analysis of the BOLD signal in functional MRI by convolving our predictors with a canonical pupil dilation response function before performing multiple regression (de Gee et al., 2014; Lempert et al., 2015b). This approach allows for better temporal resolution than a simple average.

Since our design was correlational, we are unable to draw any conclusions about the causal relationship between emotional arousal during delayed reward processing and intertemporal choice. Future studies should explicitly manipulate arousal, either pharmacologically (e.g., Sokol-Hessner et al., 2015), or through incidental arousing stimuli (e.g., Nassar et al., 2012), to determine whether emotional arousal underlies intertemporal choices in this paradigm. We also acknowledge that physiological arousal is only one component of emotion (Scherer, 2000). However, we are confident that we are capturing a positively-valenced response here, since arousal increased as the subjective value of the delayed reward increased, but not as it decreased. Future studies should investigate how other components of emotion relate to intertemporal choices, and how arousal interacts with these other components to modulate value.

Recent research in the intertemporal choice literature has revealed that temporal discounting behavior is not stable, but rather may depend on contextual manipulations (Lempert & Phelps, 2016). Emotion may play a role in these context effects; for example, when individuals think about the future in a positive light, they become more patient (Liu et al., 2013; Lebreton et al., 2013; Benoit et al., 2011). Although we did not find an overall effect of our manipulation here, we showed that emotional arousal is related to individual variability in response to this manipulation, and to the subjective value of future rewards more generally. As we learn more about the role of emotion in intertemporal choice, we can take advantage of this research to develop techniques to help people make more optimal decisions.

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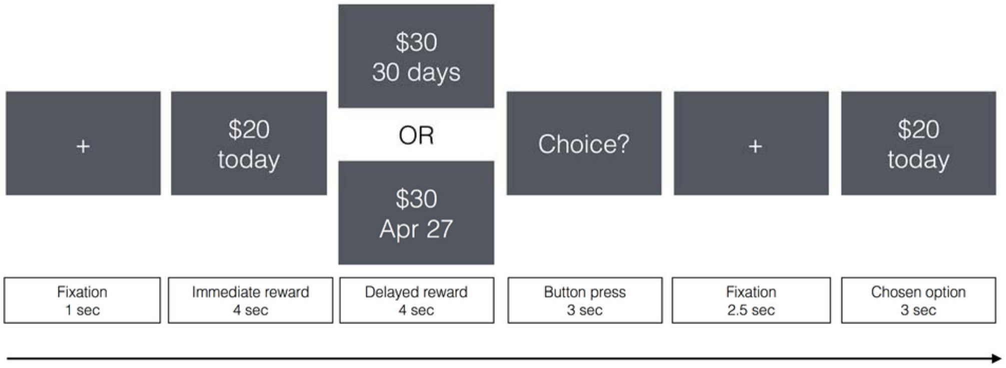

**Figure 1. Task Layout**

Each trial began with a fixation cross (1 sec), followed by display of an immediate reward option (4 sec). Then a delayed reward option was shown (4 sec). For half of the trials, it was presented with the date on which it would be received, while for the other half, it was presented with the number of days until reward receipt. Individuals made a button press while the word “Choice?” was presented on the screen following delayed reward presentation (3 sec). After another fixation cross (2.5 sec), they were shown the option that they chose on that trial (3 sec).

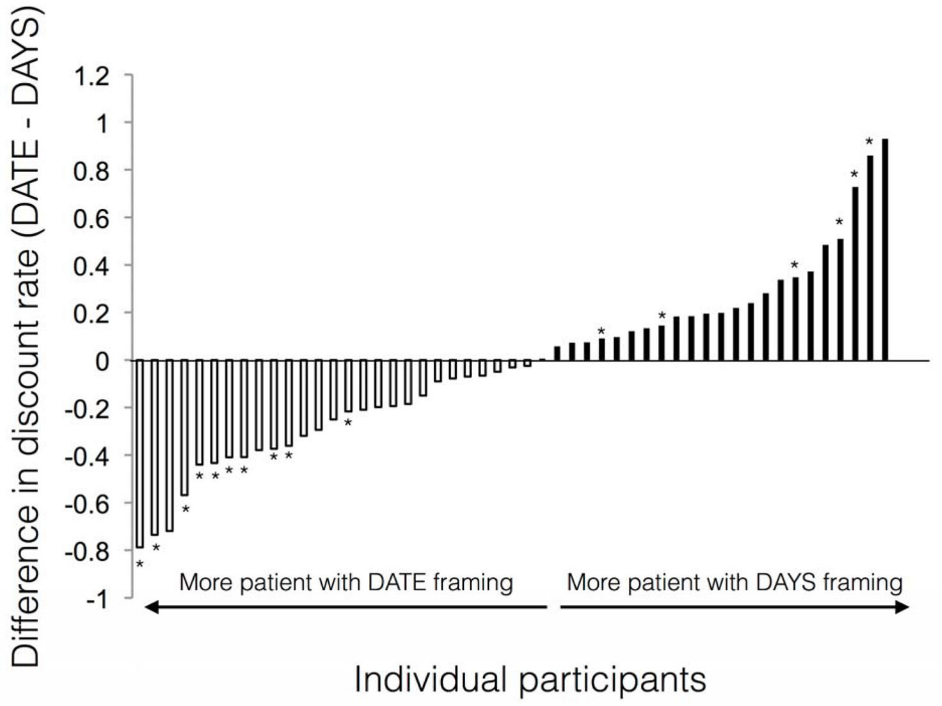

**Figure 2. Individual differences in response to DATE/DAYS manipulation**

Each bar represents the difference in log-transformed discount rate between the DATE and DAYS condition for each subject (N = 51). White bars represent subjects who were more patient (i.e., had a lower discount rate) in the DATE condition; black bars represent subjects who were more patient in the DAYS condition. Asterisks indicate subjects that showed a significant difference in discount rate between the two conditions, as determined by likelihood ratio tests (*$p < 0.05$).

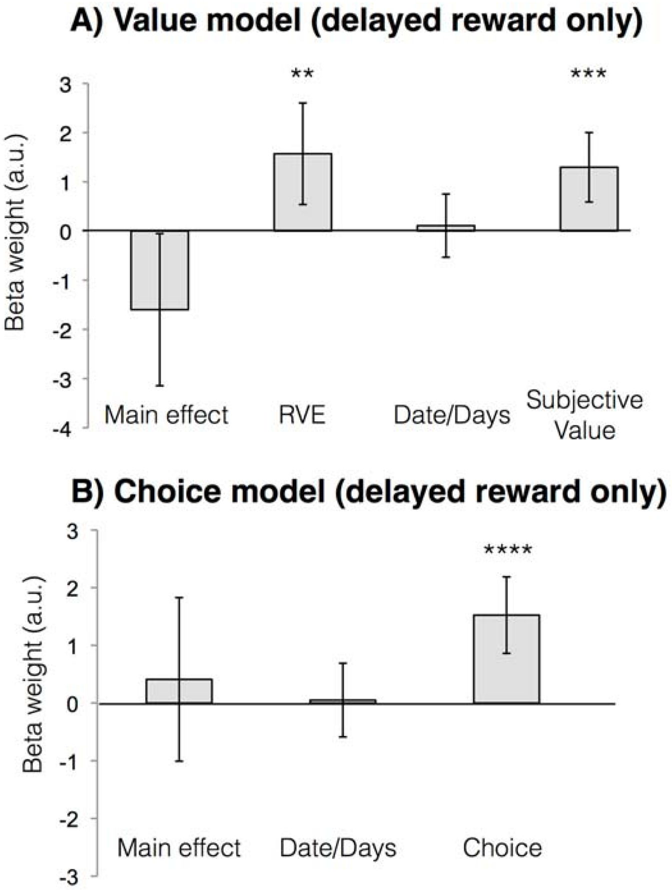

**Figure 3. Results of general linear model analysis of the pupil dilation response during delayed reward presentation**

A) Value Model. Average of best-fitting beta weights for the delayed reward presentation, and delayed reward presentation parametrically modulated by RVE (relative value equivalence: the negative of the absolute difference between the subjective values of the immediate and delayed reward options), DATE/DAYS (−1 = DAYS; 1 = DATE), and subjective value of the delayed reward. B) Choice Model. Average of best-fitting beta weights for the delayed reward presentation, and delayed reward presentation parametrically modulated by DATE/DAYS (−1 = DAYS; 1 = DATE), and choice (1 = delayed reward chosen; −1 = immediate reward chosen). Error bars represent 95% CIs (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$).

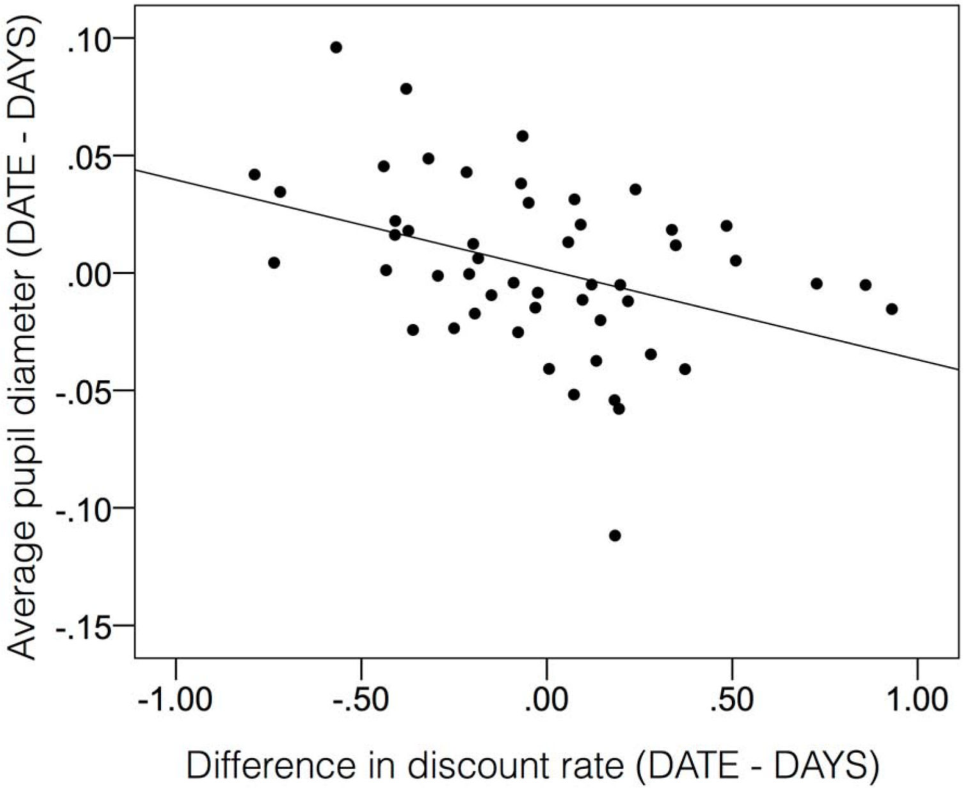

**Figure 4. Individual differences in pupil response predict individual differences in response to DATE/DAYS manipulation**

Scatterplot showing relationship between difference in log-transformed discount rate between the DATE and DAYS condition for each subject (N = 51) and difference in average pupil dilation response between the DATE and DAYS condition. Pupil dilation response was defined as the average baseline-corrected pupil diameter from 1 sec – 4 sec following delayed reward onset.

## Table 1

### Value Model results

Average of best-fitting beta weights for Value Model.

| **Predictor** | **Beta (SE)** | **Confidence Intervals** |
|---|---|---|
| *Immediate reward presentation* | | |
| Main effect | −4.1613 (1.0) *** | [−6.1765 −2.1460] |
| RVE (-abs($SV_{del}$ – $V_{imm}$)) | 0.5124 (0.37) | [−0.2360 1.2608] |
| DATE/DAYS (DATE: 1; DAYS: −1) | 0.1248 (0.22) | [−0.3262 0.5758] |
| Subjective value ($V_{imm}$) | −0.4736 (0.6) | [−1.6755 0.7284] |
| *Delayed reward presentation* | | |
| Main effect | −1.5993 (0.77) * | [−3.1455 −0.0530] |
| RVE (-abs($SV_{del}$ – $V_{imm}$)) | 1.5697 (0.51) ** | [2.6011 0.5383] |
| DATE/DAYS (DATE: 1; DAYS: −1) | 0.1090 (0.32) | [−0.5333 0.7513] |
| Subjective value ($SV_{del}$) | 1.2956 (0.35) *** | [0.5895 2.0017] |

Regressors are immediate and delayed reward presentation (main effect), and these regressors parametrically modulated by RVE (relative value equivalence: the negative of the absolute difference between the subjective values of the immediate and delayed reward options), DATE/DAYS (−1 = DAYS; 1 = DATE), and subjective value. $V_{imm}$ = value of immediate reward; $SV_{del}$ = subjective value of delayed reward.

*$p < 0.05$,

**$p < 0.01$,

***$p < 0.001$.

## Table 2

## Choice Model Results

Average of best-fitting beta weights for Choice Model.

| **Predictor** | **Beta (SE)** | **Confidence Intervals** |
|---|---|---|
| *Immediate reward presentation* | | |
| Main effect | −4.0701 (0.634) *** | [−5.3434 −2.7967] |
| DATE/DAYS (DATE: 1, DAYS: −1) | 0.1429 (0.226) | [−0.3107 0.5965] |
| Choice (Delayed: 1, Immediate: −1) | 0.2880 (0.211) | [−0.1351 0.7111] |
| *Delayed reward presentation* | | |
| Main effect | 0.3278 (0.706) | [−1.0903 1.7460] |
| DATE/DAYS (DATE: 1, DAYS: −1) | 0.1173 (0.318) | [−0.5213 0.7560] |
| Choice (Delayed: 1, Immediate: −1) | 1.5338 (0.330) **** | [0.8703 2.1972] |

Regressors are immediate and delayed reward presentation (main effect), and these regressors parametrically modulated by DATE/DAYS (−1 = DAYS; 1 = DATE), and choice (1 = delayed reward chosen; −1 = immediate reward chosen).

*** $p < 0.001$,

**** $p < 0.0001$.