The Decimal Effect: Behavioral and Neural Bases for a Novel Influence on Intertemporal Choice in Healthy Individuals and in ADHD

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Abstract

■ We identify a novel contextual variable that alters the evaluation of delayed rewards in healthy participants and those diagnosed with attention deficit/hyperactivity disorder (ADHD). When intertemporal choices are constructed of monetary outcomes with rounded values (e.g., $25.00), discount rates are greater than when the rewards have nonzero decimal values (e.g., $25.12). This finding is well explained within a dual system framework for temporal discounting in which preferences are constructed from separate affective and deliberative processes. Specifically, we find that round dollar values produce greater positive affect than do nonzero decimal values. This suggests that relative involvement of affective processes may underlie our observed difference in intertemporal preferences. Furthermore, we demonstrate that intertemporal choices with rounded values recruit greater brain responses in the nucleus accumbens to a degree that correlates with the size of the behavioral effect across participants. Our demonstration that a simple contextual manipulation can alter self-control in ADHD has implications for treatment of individuals with disorders of impulsivity. Overall, the decimal effect highlights mechanisms by which the properties of a reward bias perceived value and consequent preferences. ■

INTRODUCTION

Problems with self-control are some of the most detrimental for individuals as well as society, with obesity, excessive debt, and substance abuse representing major health and economic concerns (Madden & Bickel, 2009; Reynolds, Leraas, Collins, & Melanko, 2009; Madden, Petry, Badger, & Bickel, 1997). These issues all have one feature in common: People opt for more immediately rewarding options and undervalue future benefits to their overall detriment. To understand such phenomena, research has posited that future outcomes are evaluated using hyperbolic or quasihyperbolic discount functions, which effectively describe the tendency to overvalue immediate rewards (Frederick, Loewenstein, & O'Dohoghue, 2002). In these functions, value rapidly decreases as rewards are delayed from the present and decreases more slowly as rewards are delayed from future times.

The discount rate expressed in hyperbolic discounting is the critical factor determining relative preferences for immediate rewards. Discount rates depend on a wide variety of contextual and personal variables, such as the nature of the reward, its modality (McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007; Bickel & Marsch, 2001), its magnitude (Green, Myerson, & McFadden, 1997; Thaler, 1981), and even the scent in the experimental room (Li, 2008). Individual factors that predict differences in delay discounting include age (Steinberg, 2010; Sozou & Seymour, 2003; Green, Fry, & Myerson, 1994), health (Chao, Szrek, Pereira, & Pauly, 2009), intelligence (Shamosh et al., 2008), and some psychiatric disorders (Ahn et al., 2011; Heerey, Robinson, McMahon, & Gold, 2007). Peters and Büchel (2011) refer to these dependencies as trait (immutable, e.g., person-related) and state (mutable, framing/context) factors that affect discounting rates. The prototypical disorder associated with greater discounting and poor self-control is attention deficit/hyperactivity disorder (ADHD; Marco et al., 2009; Paloyelis, Asherson, & Kuntsi, 2009; Tripp & Alsop, 1999; Schweitzer & Sulzer-Azaroff, 1988, 1995; Rapport, Tucker, DuPaul, Merlo, & Stoner, 1986).

Process theories of temporal discounting propose a dual system model of decision-making to begin to capture the many influences on relative preferences for immediate reward (van den Bos & McClure, 2013). The first system is posited to be myopic in nature and is linked to positive emotional reactions to rewards. We use the term "affective" to represent this system (Loewenstein, 1996), which is thought to be subserved by brain areas including the

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nucleus accumbens (NAcc) in the ventral striatum, the ventromedial pFC (vmPFC), and other areas involved in evaluating rewards (Kable & Glimcher, 2007; McClure et al., 2007; McClure, Laibson, Loewenstein, & Cohen, 2004). These brain reward regions have been linked to affective responses (Knutson & Greer, 2008; Panksepp, 2004) and are thought to signal reward value in a stereotyped manner acquired through associative learning (Daw, Niv, & Dayan, 2005; Schultz, Dayan, & Montague, 1997). The second process is hypothesized to be far sighted in nature, slow and rule-based in response, but flexible enough to adaptively control behavior. We refer to this as the "deliberative" system. It is thought to be subserved by the dorsolateral pFC (dlPFC) and posterior parietal cortex (pPC; McClure et al., 2004, 2007).

Here we explore a novel effect on temporal discounting that appears to arise from differences in affective responses to reward prospects. The effect results from changing a seemingly innocuous feature of offered monetary rewards. Specifically, within-subject discount rates differ when choices are constructed from monetary rewards with rounded decimal values (e.g., \$25.00) or numbers with nonzero decimal value (e.g., \$25.12). Individuals tend to choose more impulsively when the choice is constituted of monetary rewards that are rounded numbers. We refer to this as the decimal effect. As rounded decimal amounts (\$25.00) are more common in daily experience than are nonzero decimal values (\$25.12; with .99 a possible exception), we speculate that this effect may result from greater familiarity and hence perceptual fluency with rounded dollar values (cf. Oppenheimer & Frank, 2008; Alter & Oppenheimer, 2006). Our primary aim is to provide a process account of the decimal effect. On the basis of data from several experiments, we will argue that nonzero decimal values in monetary rewards influence affective responses to the rewards and consequently influence how individuals trade off present for delayed rewards.

Our first study, Experiment 1, demonstrates the decimal effect. In Experiment 2, we show behavioral evidence that the decimal effect is related to increased positive affect to rounded monetary rewards. In Experiment 3, we provide fMRI evidence to support our main conclusions. In Experiment 4, we provide an extension of the decimal effect, testing whether rounded values have the ability to increase the value of delayed rewards. Our final study, Experiment 5, examines the decimal effect across a wide developmental period between typically developing controls and participants with ADHD.

EXPERIMENT 1

Affective processes may signal value in an automatic, stereotyped manner that is slowly acquired through experience. We hypothesized that differential experience with monetary rewards with rounded values relative to nonzero decimal values may bias how the rewards are processed by facilitating automatic responses and consequently influencing intertemporal preferences (Butterworth, 1999). We tested this prediction in our first experiment.

Methods

Participants

We recruited 28 participants; 12 at Stanford University (eight men, mean age = 20.26 years, range = 18–22 years) and 16 from Baylor College of Medicine and the greater Houston area community (10 men, mean age = 26.38 years, range = 20–36 years). (See Table 1 for inclusion/exclusion criteria for all studies and Table 2 for demographic data for Experiments 1–4.) We excluded one participant from each site because they failed to submit choices on all trials. Participants from Baylor College of Medicine completed the task while undergoing fMRI scanning (see Experiment 3).

Materials

Each participant was presented with 62 intertemporal choices offering an immediate reward and a larger but delayed reward. For half of the choice trials, rewards had rounded decimal values (e.g., \$11.00 today or \$21.00 in 6 weeks; rounded condition). The other half had only nonzero decimal values (e.g., \$10.87 today or \$20.74 in 6 weeks; decimal condition). We omitted decimal values of .25, .50, .75, and .99, as these are common numbers and may have intermediate effects between our rounded and nonzero decimal values. Trials were presented in random order.

The choice trials were derived from the hyperbolic discounting function (Mazur, 1987) that models subjective value as a function of delay according to the function,

$$V = \frac{r}{1 + kd}, \qquad (1)$$

where r is the magnitude of the reward, d is the delay until receipt, and V is the discounted value. For each trial, a unique discount rate, k_{eq}, implies indifference between the immediate reward and the discounted, delayed reward. Choices were constructed so that each trial in the rounded condition matched a trial in the decimal condition with an equal discount rate (k_{eq}) and delay. For the rounded value rewards, magnitudes spanned a range of \$2 to \$33; nonzero decimal values ranged from \$2.14 to \$32.90. Delayed rewards were available between 7 and 56 days in the future (in 7-day increments). Reward magnitudes could not be exactly equated; thus, half of the decimal values were slightly larger and the other half slightly smaller than their rounded pairs. As it was not possible to make the average magnitudes exactly the same, decimal values were on average 18¢ (±\$1.33) smaller than rounded values. This design ensured that both conditions

Table 1. Inclusion/Exclusion Criteria for All Experiments

Group	*Experiments 1–4*
Inclusion Criteria	
HC	Ages 18–50
Exclusion Criteria	
HC	Clinical history of neurological, major medical or psychiatric disorder fMRI contraindications[a]
	Experiment 5
Inclusion Criteria	
HC and ADHD	Ages 12–30 IQ over 80 as per WASI
HC	*t* score of 60 or lower on the total DSM total ADHD score
HC	3 or more inattentive and 3 or more hyperactive/impulsive DSM symptoms
ADHD	*t* score of 65 or higher on the total DSM total ADHD score
ADHD	6 or more inattentive and 6 or more hyperactive/impulsive DSM symptoms
ADHD	Significant symptoms before age 7 and across at least two domains (e.g., home and school/work)
Exclusion Criteria	
HC and ADHD	Any Axis 1 disorder except for ADHD in the ADHD group
HC and ADHD	Clinical history of neurological, major medical of psychiatric disorder
HC	History of treatment with psychoactive medication
HC[a]	fMRI contraindications

HC = healthy control.

[a]Exclusion for Experiment 3.

spanned the same range of intertemporal trade-offs, while controlling for any bias because of differences in reward magnitude (Thaler, 1981).

Procedure

Participants had unlimited time on each trial to make their choice. A 2000 msec blank intertrial interval was used (see Figure 1A). The 62 trials were split into four blocks of either 15 or 16 trials, with one 15 trial and one 16 trial block for both the rounded and decimal conditions. Block order was counterbalanced according to condition, with half of participants beginning with rounded and ending with decimal trials. Trial order within each block was randomly generated.

Table 2. Demographic and Clinical Characteristics for Participants in Experiments 1–4

Experiment	*Group*	*Age*	*Age Range*	*Gender (male)*	*n*
1	HC	22.4	18–36	17	42
2	HC	29.5	19–50	19	40
3	HC	26.1	20–36	9	16
4	HC	35.5	19–45	92	183

Data are summarized as mean for the continuous variables.

We used a lottery system in which one of the participant's choices was randomly selected and paid to the participant according to the amount and delay of the selected choice. Participants were instructed to consider each choice seriously as any one could potentially be paid according to their selection. This encouraged participants to remain focused throughout the experiment and to treat all trials as equally determinant of their overall earnings.

Estimation of Discount Rates

For each participant and condition, discount rates were estimated by maximum likelihood. Participants' binary

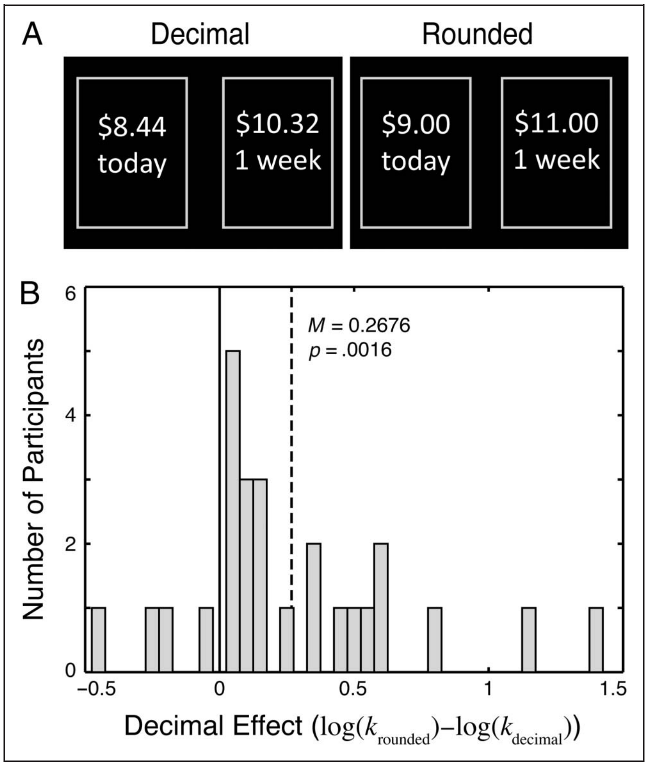

Figure 1. (A) Intertemporal choices for monetary outcomes with nonzero and rounded decimal values elicit different temporal discount rates. (B) Discount rates are consistently higher for rounded dollar values across participants, producing a robust mean decimal effect.

choices between the immediate and delayed rewards were modeled with the exponential version of the Luce choice model (Luce, 2005). If we summarize the subjective value of the two alternatives as V_1 and V_2 for the immediate and delayed rewards, respectively, then the probability of choosing the immediate outcome for an arbitrary k is given by

$$P(Choose\ V_1) = (1 + \exp(-mV_\Delta(k))^{-1} \qquad (2)$$

where $V_\Delta(k)$ is the difference $V_1 - V_2$ for some value of k. Likewise, the probability of choosing the delayed outcome is equal to $1 - P(Choose\ \ V_1)$. The parameter m captures how consistent choices are with the fitted discount function.

The likelihood of any set of choices per participant is the product of the probability for each observed choice. For each condition (c), we form the likelihood function,

$$L_c(m,k) = \prod_{s=1}^{S}\prod_{i=1}^{N} P_{i,s}(Choose\ V_1)^J\,(1 - P_{i,s}(Choose\ V_1))^{1-J} \qquad (3)$$

where $J = 1$ if the immediate reward is chosen and zero otherwise. We maximized Equation 3 with respect to k and m using a simulated annealing optimization algorithm. This yields condition-specific estimates for k and m. The standard errors of the estimates were obtained by invoking the asymptotic normality of the maximum likelihood estimators.

Results

Choices revealed the decimal effect: Participants made more impulsive decisions in the rounded relative to the decimal condition. We performed analyses on log-transformed discount rates using nonparametric tests because the distributions of log(k) were nonnormal (Kolmogorov–Smirnov tests, $p < .001$ for both decimal and rounded conditions). The decimal effect held among 22 of our 26 participants (see Figure 1B). Moreover, discount rates in both the decimal and rounded conditions were not significantly different across participants recruited from Stanford University and Baylor College of Medicine (Wilcoxon rank sum test; $p > .24$ comparing discount rates in rounded and decimal conditions). We therefore analyzed data collectively across these two groups. Comparing the estimated discount rates across conditions within participants, the mean of the differences between the log-discount rates in the rounded versus decimal conditions is positive (0.27) and significantly different from zero (sign test, $p < .001$).

We ruled out two potential confounds associated with the decimal effect. First, we found no difference in RT between the two conditions (mean RT rounded = 3273.04 msec; mean RT decimal = 3088.59; mean rounded − decimal = 184.45 msec, *SE* 138.59, $t(25) = 1.28$, $p > .20$). Second, choice consistency was not influenced by task condition. Comparing m values indicated no significant difference (Wilcoxon signed rank test $p = .67$). Likewise, fitted k values predicted an average of 90.12% and 88.34% of choices in the decimal and rounded conditions, respectively (Wilcoxon signed rank test, $p = .17$).

Reward magnitude is also known to influence discount rates (e.g., Thaler, 1981). To rule out an influence of magnitude on our results, we split choices (by median) into low- and high-magnitude trials, collapsing across decimal conditions. We then estimated k separately for low- and high-magnitude choices per participant. We performed a sign test on the difference in log(k) values across magnitudes and found no significant difference ($p = .33$).

Discussion

Consistent with our hypothesis, we found that the nature of the decimal values in monetary rewards influenced intertemporal preferences. We suggested that monetary rewards containing rounded values would be more perceptually fluent and therefore trigger affective valuation processes to a greater degree than would nonzero decimal values. As affective processes are thought to be myopic in nature (Loewenstein, 1996), this would account for our observed differences in discount rates.

EXPERIMENT 2

Experiment 2 tested the hypothesis that rounded dollar values differ from nonzero decimal values on the basis of affective response. We primed affective processes by asking participants to rate their emotional reaction (Hsee & Rottenstreich, 2004) to the prospect of winning different amounts of money to determine how rounded and nonrounded monetary rewards are evaluated using emotionally based valuation. We manipulated decimal values while holding magnitude comparable. We hypothesized that if valuation of round numbers involves more affective processing, round numbers would generate greater positive affect than comparable nonzero decimal numbers. The alternative hypothesis is that affective processes are unaffected by decimal value, in which case affect ratings between rounded and nonzero decimal values should not differ.

Methods

Participants

A total of 54 volunteers were recruited (25 men; mean age = 28.8 years) from the Stanford community and gave written informed consent to participate. Because of a technical error in conducting the experiment, 14 participants did not complete all of the ratings and thus were excluded, leaving 40 participants for analyses.

Materials and Procedure

In accordance with the two-dimensional affective circumplex model of emotion (Watson, Wiese, Vaidy, & Tellegen, 1999; Watson & Tellegen, 1985), we separately assessed valence and arousal to measure the subjective emotional impact of rounded versus decimal monetary rewards. Participants received an online questionnaire, asking them to make subjective assessments of 10 monetary rewards, five rounded and five with nonzero decimal values. Each rounded reward was matched to a decimal reward; in each pair, the rounded number had a smaller objective value. Each of the 10 numbers was presented in a random order, and participants were asked the following questions:

> Imagine you have the chance to win $25.00.
> How Positive or Negative would you feel?
> How Activated/Aroused would you feel?

Participants answered the questions using sliding scales numbered from 0 to 100 and anchored to 50 on presentation of the question.

Results

As valence (v) and arousal (a) ratings were significantly correlated in our data ($r^2 = .54, p < .0001$), we combined these measures on a single dimension of positive arousal as our primary variable of interest ($\text{PA} = (v + a)/\sqrt{2}$; based on Knutson & Greer, 2008). A two-way, within-subject ANOVA was conducted to compare the main effects of (1) condition (rounded vs. decimal values) and (2) reward magnitude for participants' affect ratings for rewards. We found greater PA for rounded values with a significant main effect of condition, $F(1, 38) = 5.48, p = .03$. We also found a significant main effect of reward magnitude on PA ratings, $F(4, 38) = 29.82, p < .001$, with larger values eliciting more positive ratings. These results are shown in Figure 2, where we have plotted normalized ratings (z score corrected within participants across conditions) as a function of reward amount. The interaction between condition and reward magnitude was not significant ($p = .18$).

Similar results held when valence or arousal were analyzed using similar ANOVAs. For valence, there was a main effect of amount, $F(4, 38) = 30.50, p < .001$, and condition, $F(1, 38) = 4.98, p = .03$, but no significant interaction ($p = .38$). For arousal, there was a main effect of amount, $F(4, 38) = 23.96, p < .001$, and a trend for condition, $F(1, 38) = 3.43, p = .07$, with no significant interaction ($p = .23$).

Because of the large age range in our participants, we conducted additional ANOVA analyses looking for a main effect of age (split into quartiles) or an Age × Reward magnitude interaction. We found no significant differences on the basis of participants' age ($p > .46$ for both analyses).

Discussion

These results suggest that participants feel more positive arousal for monetary rewards with rounded compared

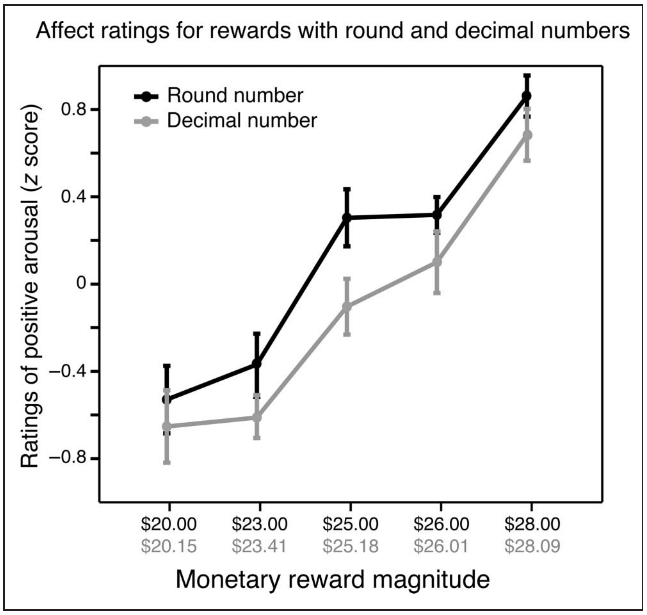

Figure 2. Positive arousal reported for the prospect of earning a rounded dollar amount was larger than that reported for nonzero decimal values or marginally greater objective value. Data have been normalized within participants (z score transformed); error bars are standard errors of the mean.

with those with nonzero decimal values. Not surprisingly, they also reported feeling more positive arousal for greater magnitudes of monetary rewards. Importantly, this differential affective response overcomes the fact that rounded values were smaller in objective value.

EXPERIMENT 3

Properties linked to affective and deliberative processes distinguish the functions of the NAcc and dlPFC in intertemporal choice (Peters & Büchel, 2011; McClure et al., 2004). Affective responses to rewards and related NAcc activity predict individual discount rates (Hariri et al., 2006). Cognitive ability correlates with dlPFC activity and lower discount rates (Shamosh & Gray, 2008; Shamosh et al., 2008). Furthermore, manipulating these systems either pharmacologically (Pine, Shiner, Seymour, & Dolan, 2010) or by direct stimulation (Figner et al., 2010) alters discount rates in the expected directions. In this study, we measure correlates of affective and deliberative processing while participants make intertemporal choices containing rounded or nonzero decimal values. Given the results from Experiment 2, we conjectured that rounded values would more effectively recruit the NAcc than would nonzero decimal values. fMRI also allows us to test whether rounded and decimal values differentially recruit deliberative processes by measuring activity in the dlPFC and pPC.

Methods

Participants

Out of 28 participants in Experiment 1, the 16 participants from Baylor College of Medicine performed the task while undergoing fMRI scanning. The two participants excluded from the analysis in Experiment 1 were from this group of 16.

Materials and Procedure: Behavioral Task

Experimental materials and procedures were similar to Experiment 1, except that a 12-sec intertrial interval was included to accommodate the BOLD signal. Participants were paid as in Experiment 1 plus $20 base pay for the fMRI.

fMRI Study Procedure

Brain images were acquired using a 3-T Siemens Trio MR Scanner at Baylor College of Medicine. A high-resolution ($1 \times 1 \times 1$ mm^3) T1-weighted anatomical image was first acquired. For functional images, T2-weighted EPIs were acquired (repetition time = 2 sec, echo time = 30 msec, flip angle = 90°; data acquired approx. 30° off the AC–PC line, 37 slices with 2 mm gap, 64×64 matrix, 3.0 mm^3 isotropic voxels). Data preprocessing and linear regressions were conducted with SPM5. ROI analysis was performed with AFNI using spherical masks of 12 mm diameter. Preprocessing included slice-time correction, realignment, spatial normalization, and smoothing with an 8 mm FWHM Gaussian kernel. Volumes were normalized to the Montreal Neurological Institute template and resampled at $4 \times 4 \times 4$ mm^3 isotropic resolution.

Whole-brain general linear model analyses fit hemodynamic responses with a boxcar activation function with RT indicating trial duration and onset given by choice presentation onset. Differences in RTs across choices were thus explicitly modeled. Movement parameters were modeled as covariates of no interest.

Results

Given that trials in the two conditions were paired, a subtraction of the mean brain response across the two conditions reveals the difference in brain activity in rounded versus decimal value choices. One confound with this subtraction is that choices themselves are different and may affect brain activity. We controlled for choice in two ways. Linear models were fit with a nuisance regressor that indicated the choice outcome (immediate or delayed reward). We also conducted hierarchical analyses where a linear model was first fit for choice outcome alone. The fitted choice-related responses were then subtracted from the original data and the residual signals were subjected to a linear model to fit average responses in rounded and decimal trials. Because the two approaches yielded qualitatively identical results, we only present the results with choice included as a nuisance regressor in this discussion.

Two separate analyses were conducted to examine the effect of nonzero decimal versus rounded numbers on brain activity in intertemporal choice. First, an omnibus general linear model analysis was performed on the whole brain, coregistered data. This analysis revealed three brain regions that had significantly greater activity in the rounded relative to the decimal condition ($p < .05$, corrected for multiple comparisons by false discovery rate). We omit from further discussion one region identified in the right ventrolateral temporal lobe that has not previously been associated with reward processing (peak Montreal Neurological Institute coordinates −60, −56, −4). The other two regions were in the left and right NAcc (Figure 3A; 20, 10, −12 and −16, 10, −12, respectively).

Second, we created individual masks on nonnormalized data to select the bilateral NAcc and directly analyzed the average activity within this anatomical region. The ROI analysis from subject-specific NAcc confirmed the results of the whole-brain analysis. The difference in NAcc activity measured across participants correlated with the size of the behavioral decimal effect (i.e., $\Delta\log(k) = \log(k_{\text{round}}) - \log(k_{\text{decimal}})$). Participants with greater NAcc activity in the rounded compared with the decimal

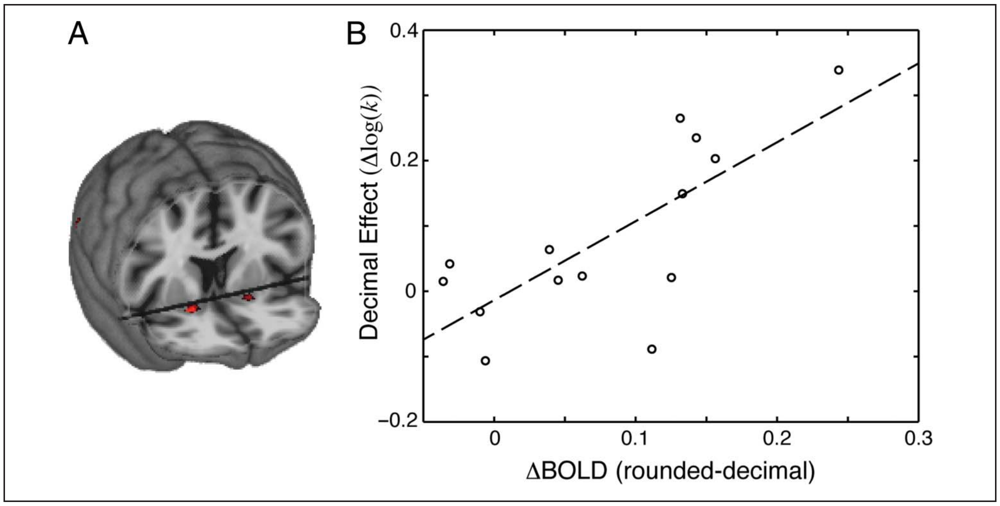

Figure 3. (A) Whole-brain analyses indicate that, on average, the NAcc (bilaterally) is more activated as participants make intertemporal choices with rounded values compared with choices with nonzero decimal values. (B) The NAcc was identified in individual participants using anatomical MRI images. Mean event-related responses in the bilateral NAcc correlated with the size of the decimal effect across individuals ($\Delta\log(k) = \log(k_{\mathrm{round}}) - \log(k_{\mathrm{decimal}})$).

condition showed larger increases in discounting rates in the rounded compared with the decimal condition (see Figure 3B; $r = 0.74$, $p = .002$). The result holds when omitting the outlier participant at the top right of the plot ($r = 0.62$, $p = .02$) and when performing a robust regression ($p = .002$).

Finally, we had an a priori interest in the dlPFC and pPC given previous work (Figner et al., 2010; Hare, Camerer, & Rangel, 2009; McClure et al., 2004, 2007). No regions in either the dlPFC or pPC were significant in our whole-brain analyses, even at the liberal threshold of $p < .1$. We therefore specifically looked at average activity in ROIs of 12 mm diameter spheres based on regions identified in previous studies (dlPFC: McClure et al., 2004, 44, 44, 16, and Hare et al., 2009, −48, 15, 24; pPC: McClure et al., 2004, −8, −28, 32). There were no significant differences in rounded minus decimal values for any of these locations (dlPFC: $p = .45$ and .37, respectively; pPC: $p = .55$). Furthermore, the trend was for greater dlPFC and pPC activation for choices involving rounded numbers whereas the prediction from behavior would be less activation for rounded compared with nonzero decimal values.

Finally, other brain areas were of a priori interest because they have been implicated in reward processing in other studies. Thus ROI analyses were conducted on the vmPFC, amygdala, and hippocampus. The vmPFC is commonly identified in fMRI studies of temporal discounting (see Peters & Büchel, 2010, for a review; ROIs from McClure et al., 2004, 0, 44, 12; Hare et al., 2009, 3, 36, −12). Likewise, the amygdala has been implicated in reward processing (ROI from Knutson, Adams, Fong, & Hommer, 2001) and the hippocampus is implicated in evaluating stimuli (ROI from Wimmer & Shohamy, 2012). We found no significant difference between conditions at either of the vmPFC locations ($p > .35$ for responses averaged over 12-mm-diameter spheres centered at the indicated locations). Similarly we found no significant differences in the hippocampus ($p = .22$) or in the amygdala ($p = .31$). In these latter two regions, the trend was toward greater activity for choices involving decimal values relative to rounded values, contrary to our findings for the ventral striatum.

Discussion

Our prediction from examining choices between monetary outcomes was that intertemporal choices with rounded values would preferentially recruit brain reward areas, particularly the NAcc. This prediction was supported by the further finding that the degree of activity in the NAcc correlated with individual differences in the decimal effect.

"Affective" and "deliberative" modes of valuation are constructs intended to capture aspects of behavior. Although there is certainly a link between the properties of these constructs and the function of the NAcc, dlPFC, and pPC, there are substantial differences as well (van den Bos & McClure, 2013). Nonetheless, fMRI allowed us to test for differential involvement of functionally disparate brain systems during intertemporal choices. We confirmed that the affect-related NAcc is differentially recruited during presentation of rounded values. Furthermore, we find no evidence of differential recruitment of brain areas associated with deliberative processes. Conclusions from this latter finding should be tempered by acknowledging limited power (especially when asserting a null hypothesis); fMRI has relatively low signal-to-noise ratio. Additionally, the dlPFC and pPC are large brain regions whose organization is not well understood. We found no difference in activity in either of these cortical areas even at very liberal statistical thresholds, but additional work is necessary to confirm this finding.

The vmPFC may integrate multiple influences contributing to total subjective value (Rangel & Hare, 2010). The vmPFC receives (primarily indirect) inputs from both the NAcc and dlPFC (Hare et al., 2009) and activity in the vmPFC correlates with time-discounted value (Kable & Glimcher, 2007). Here, the vmPFC displayed a subtle dependence on rounded values in the subgenual cingulate cortex near that area associated with subjective value

(Rangel & Hare, 2010). However, the effect in the vmPFC was notably weaker than in the NAcc, suggesting that the decimal value influences temporal discounting by influencing the type of primary motivations represented in the NAcc.

EXPERIMENT 4

In Experiment 1, we demonstrated that participants were more likely to choose a larger, delayed over a smaller sooner reward when presented with nonzero decimal values. In Experiment 2 we established that participants did not feel as positively aroused to nonzero decimal values compared with rounded values. Therefore, it may be that the decimal effect arises from preferential affective responses to monetary rewards with rounded values. This effect may act in concert with the myopia generally assumed for the affective system in intertemporal choice to increase discount rates. The NAcc is preferentially activated by immediate rewards but also maintains some response to delayed outcomes (Kable & Glimcher, 2007; McClure et al., 2004). Similarly, emotional responses are generally far greater to immediate overdelayed outcomes (Loewenstein, 1996), but delayed rewards still induce positive affect. This raises the question of whether coupling rounded values to delayed rewards can enhance an otherwise diminished affective response to the benefit of more far-sighted decision-making. In Experiment 4, we test this idea by crossing decimal value (rounded vs. nonzero decimal) with time (immediate vs. delayed).

Methods

Participants

We recruited a total of 200 participants using Amazon's Mechanical Turk. Participants were restricted to be native English speakers and to reside in the United States. We obtained informed consent before participants completed the task. We excluded 17 participants because they selected all smaller, sooner or larger, later choices. This left 183 eligible participants (92 men; mean age = 35.52 years). Participants were randomly assigned to one of two conditions, the rounded-immediate ($n = 91$) or the rounded-delayed condition ($n = 92$).

Materials and Procedure

All participants completed two temporal discounting questionnaires, presented via computer, with hypothetical reward choices. Each question offered a choice between a particular amount of money today and a larger amount of money after a certain number of days. Participants were instructed to evaluate the questions as if they would actually receive the amount of money at the time specified in the choice. However, the choices were hypothetical in nature and did not influence payments. All participants completed the same control questionnaire, which consisted of the same choices as constituted the nonzero decimal choices in Experiment 1. Participants completed a second 31-item temporal discounting questionnaire that followed the same structure but differed slightly based on experimental condition. In the rounded-immediate condition, all of the monetary rewards offered today were round numbers (ranging from \$2.00 to \$31.00), whereas the monetary rewards offered later had nonzero decimal values (ranging from \$2.97 to \$38.34). In the rounded-delayed condition, all of the monetary rewards offered later were round numbers (ranging from \$2.00 to \$32.00), whereas the monetary values offered immediately had nonzero decimal values (ranging from \$1.34 to \$31.09). As in Experiment 1, values for immediate amounts, delayed amounts, and delay length were calculated according to Equation 1 to be matched between conditions on discounting rate, k_{eq}, and to share similar reward magnitudes and delays. Delay lengths ranged from 7 to 56 days as in Experiment 1. The order of control and experimental questionnaires was counterbalanced between participants for both conditions and trials were presented in random order. Measures of temporal discounting were calculated by maximum likelihood as described for Experiment 1.

Results

Our dependent measure was the difference in the log-discount rates across experimental and control conditions. As the log-transformed values were not normally distributed (Kolmogorov–Smirnov test for normality; $p < .05$ for both conditions), we performed nonparametric Wilcoxon signed rank tests. These analyses replicated our previous finding that immediately available rounded values increase discount rates ($p = .008$; mean RT control = 3075.3 msec; mean RT rounded = 2735.2 msec; mean rounded − control = 340.1 msec, $SE = 383.3$ msec). However, we find no change in discounting with rounded-delayed outcomes ($p = .90$; mean RT control = 2737.3 msec; mean RT rounded = 2684.6 msec; mean rounded − control = 52.7 msec, $SE = 116.0$ msec). A two-sided rank sum test indicates that the effect on discount rates was moderately greater for the rounded-immediate than the rounded-delayed condition ($p = .06$). There was no difference in choice consistency across rounded-immediate and rounded-delayed conditions (rank sum test of m value estimates across rounded and control conditions, $p = .54$).

Discussion

This experiment demonstrates a close coupling between the influence of the affective impact of rewards on temporal discounting and immediacy. In particular, we find that changing decimal values only impacts intertemporal preferences when the rounded value is available immediately. It is certainly possible that decimal value may influence the evaluation of delayed rewards and that this experiment simply suffers from lack of power. Thus, we hesitate to conclude that rounded decimal values have no effect on delayed rewards—but instead believe that rounded values preferentially impact the evaluation of immediate outcomes.

EXPERIMENT 5

Temporal discounting is tempered by individual and external contextual factors (van den Bos & McClure, 2013; Peters & Büchel, 2011). Individual factors that predict differences in behavior include age and the symptom domain of hyperactivity/impulsivity (Scheres & Hamaker, 2010; Scheres, Tontsch, Thoeny, & Kaczkurkin, 2010; Scheres, Lee, & Sumiya, 2008; Thorell, 2007). However, developmental findings in temporal discounting are inconsistent (Christakou, Brammer, & Rubia, 2011; Prencipe et al., 2010), perhaps because the age ranges studied tend to be wide and/or they do not systematically assess other contextual factors. Differential maturation rates of brain systems underlying decision-making may underlie changing self-control across lifespan. Some of these regions (e.g., NAcc, vmPFC, and dlPFC) have also been linked to ADHD impairment (Costa Dias et al., 2013; Scheres, Milham, Knutson, & Castellanos, 2007; Dickstein, Bannon, Castellanos, & Milham, 2006). In this final experiment, we examined self-control across a crucial time of brain development where there are greater expectations for self-management (12–30 years). We hypothesized that decimal values would affect self-control choices in both control and ADHD groups. Moreover, we predicted that younger children, in general, would display less self-control, reflected by a greater tendency to select the smaller, sooner rewards, than would older participants.

Methods

Participants

A group of 40 typically developing individuals and a group of 25 individuals diagnosed with ADHD, Combined Type (i.e., significant symptoms of inattention and hyperactivity/impulsivity) were recruited through the UC Davis MIND Institute. All participants gave written informed consent or verbal assent in addition to written consent from a parent or guardian in the case of minors (see Table 3 for demographic and clinical information). We included 12 years old as our minimum age because children younger than 12 are less likely to be able to fully appreciate monetary value and conceptualize the temporal delays presented within the paradigm. Participants were randomly assigned to one of two presentation orders, the rounded condition first (n = 31) or the decimal condition first (n = 34).

Materials and Procedure

A similar set of intertemporal choices was presented to participants as in Experiment 1. As real rather than hypothetical rewards are thought to pose more of a challenge

Table 3. Demographic and Clinical Characteristics for Participants in Experiment 5

	ADHD (n = 25)	*Healthy Controls (n = 40)*	*Total (n = 65)*
Demographic Characteristics			
Gender			
Female	13 (52%)	17 (43%)	30 (46%)
Male	12 (48%)	23 (58%)	35 (54%)
Age	18.6 (5.7)	17.6 (4.1)	18.0 (4.8)
Age range	12–30	12–28	12–30
Clinical Characteristics			
FSIQ[a]	115.2 (14.3)	117.3 (11.1)	116.4 (12.4)
Letter–Word Identification Score[a]	109.0 (12.1)	110.6 (9.0)	110.0 (10.3)
Math Calculation Score[a]	110.2 (12.5)*	117.0 (12.6)*	114.3 (12.9)
DSM Inattention Subscale Score[b]	79.3 (12.7)*	45.6 (6.4)*	58.8 (19.0)
DSM Hyperactive-Impulsive Subscale[b]	79.7 (12.8)*	45.3 (4.2)*	58.7 (18.9)

Data are summarized as mean (*SD*) for the continuous variables and frequency (%) for gender. FSIQ = Full-scale Wechsler Abbreviated Scale of Intelligence.

*Wilcoxon two-sample test $p < .05$.

[a] Frequency missing in healthy control group = 2.

[b] Frequency missing in healthy control group = 1.

Table 4. Summary of Mixed Effects Model Examining the Relationship of Group, Condition, Age, and Gender to Delay Discounting

	Estimate (SE)	*p*
Model Term		
Intercept	0.054 (0.008)	< .001
Group (ADHD)	0.028 (0.011)	.019
Condition (nonzero decimal)	−0.009 (0.003)	.004
Age	−0.003 (0.001)	.027
Gender (female)	−0.015 (0.011)	.161

to self-control in ADHD (Scheres et al., 2008), we employed a lottery system as in Experiment 1. Each individual's discount factor, *k*, was calculated as outlined above. Statistical analyses employed mixed effect models implemented in SAS Version 9.3. (using PROC MIXED), because they accounted for the correlated structure of the data because of repeated measures of delay discounting within participant (i.e., rounded and decimal trial types). This approach accommodated three instances of missing data (data excluded due to participants uniformly choosing either the immediate or delayed rewards). The core model predicting *k* included main effects for group (ADHD and control), condition (rounded and nonzero decimal), terms for age and gender, and a random effect for individual. Model assumptions were validated both graphically and analytically (Table 4).

Results

The analysis revealed a main effect of group, $F(1, 41.61) = 5.99$, $p = .02$, with the ADHD group showing significantly greater discount rates (*k*) than the control group. There was also a main effect of condition, $F(1, 60.52) = 8.82$, $p = .004$, with participants displaying the decimal effect (greater impulsivity in the rounded condition; see Figure 4). As predicted, age was also significantly related to delay discounting, with younger age associated with larger discount rates, $F(1, 60.12) = 5.17$, $p = .03$. There was neither a significant effect of gender on discount rates, $F(1, 57.45) = 2.02$, $p = .16$, nor a significant Group × Condition interaction ($p > .7$).

Discussion

These results replicate our main finding that decimal values influence discount rates—even in those with elevated levels of impulsivity, such as ADHD. The tendency to favor immediately available rewards plays a central role in the delay aversion theory (Sonuga-Barke, Taylor, Sembi, & Smith, 1992) and the steeper and shorter delay-of-gratification gradient theory of ADHD (Sagvolden, Aase, Zeiner, & Berger, 1998). Our replication of the decimal effect in impulsive individuals is particularly significant for populations who display a greater tendency to select immediate rewards, such as adolescents and individuals with substance dependence (Madden & Bickel, 2009). Increased discounting is linked to poor health outcomes and reduced academic achievement and occupational success (Golsteyn, Gronqvist, & Lindahl, 2013). Attempting to improve self-control in individuals with heightened impulsivity by altering reward perception would be a novel approach for reducing the negative outcomes associated with impulsivity. Treatment of ADHD and substance use disorders currently involves contingency management in which rewards are given for appropriate behavior (e.g., Bickel et al., 2010; Barkley, 2006). Although the size and delay of the rewards are typically considered in developing a behavior plan, it has not been considered how to best frame or present rewards in these plans. Our findings suggest that future research should assess how framing effects could enhance the value of delayed rewards to increase self-control across conditions associated with impulsivity.

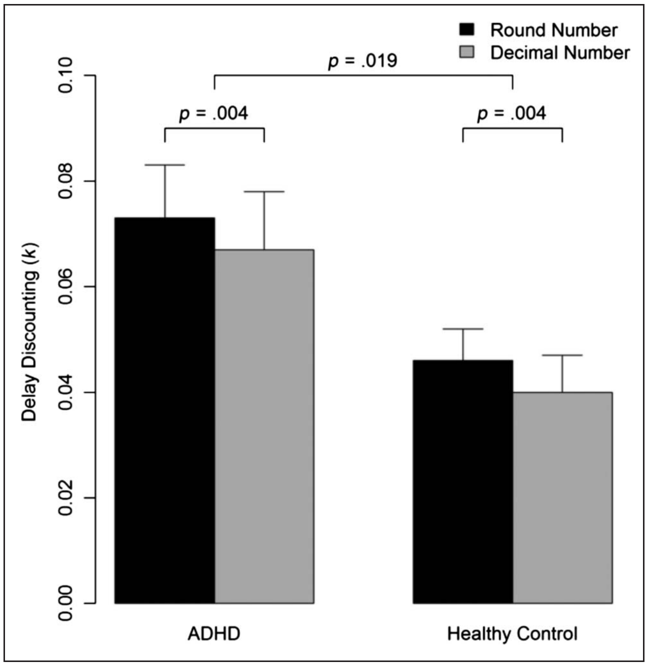

Figure 4. Rates of impulsive decision-making (*k*) on a delay-discounting task using real rewards are displayed for individuals with ADHD and typically developing controls across two different conditions. In both conditions, participants were presented with choices between a relatively small immediate monetary reward or a larger, delayed monetary reward. In the round number condition, monetary values were presented as a dollar amount only (e.g., $5.00), whereas in the decimal number condition, these values were presented as dollars and cents (e.g., $5.03). The ADHD group made more impulsive choices than the typically developing control group overall, in that they chose the immediate reward over the larger, delayed reward more often. Introduction of the decimal condition reduced impulsivity in both the ADHD and control groups, meaning that, in both groups, individuals tended to choose the larger, delayed reward more often when the amount was presented as dollars and cents rather than simply in dollars alone.

We also replicate the finding that younger individuals have higher discount rates than do older people, independent of the presence or absence of ADHD (Steinberg et al., 2009). Casey and colleagues (Casey, Duhoux, & Malter Cohen, 2010; Casey, Jones, & Hare, 2008) propose that an increase in risky behavior during adolescence is because of an imbalance between relatively more mature, subcortical brain systems versus less mature functioning in cortical regions linked to cognitive control. Studies suggest impaired modulation of hyperactive reward-related striatal regions by cognitive control regions (i.e., dlPFC) in adolescence (Christakou et al., 2011; Van Leijenhorst et al., 2010; Berns, Moore, & Capra, 2009; Galvan et al., 2006). Brain regions linked to self-control and evaluation of future outcomes (Galvan et al., 2006) mature later in development (e.g., Christakou et al., 2011; Cohen et al., 2010; Olson et al., 2009). Optimal connectivity between dlPFC and other regions (pPC, vmPFC) to support more self-controlled behavior putatively occurs in adulthood (Luna, 2009). Regions such as the NAcc, which have been associated with more impulsive choices in Experiment 3, have also been consistently implicated in ADHD impairments (Hart, Radua, Nakao, Mataix-Cols, & Rubia, 2013; Scheres et al., 2007).

GENERAL DISCUSSION

Emotional responses have long been hypothesized to underlie the short-sighted behavior evident in choices involving tempting immediate rewards (Loewenstein, 1996; Mischel, 1974). We identify a novel effect on delay discounting consistent with this assertion: subtle features of prospective rewards can change affective responses and impatience.

A large number of effects influence how intertemporal preferences are formed (van den Bos & McClure, 2013). One potential unifying framework for understanding these diverse influences may come from positing independent neurocognitive systems that underlie the evaluation of rewards. We refer to one common dichotomy of such systems herein as affective and deliberative. We have shown that such a framework can explain how a relatively innocuous feature of an intertemporal choice, the numbers following the decimal point, comes to influence discounting. We combined behavioral and neural measures to test how decimal values alter the affective responses that distinguish these two modes of valuation. Overall, we have established a pathway whereby properties of a reward influence consequent discount rates. Although it is possible that the decimal effect is better explained by other effects such as subtle differences in sensory processing or calculation of numerical differences between the rounded and decimal conditions, we believe this is less likely. We found no evidence in to support differences between the rounded and decimal conditions in visual or sensory brain regions nor in decision-related RTs.

It remains to be seen whether the dual system framework will be sufficient to account for the number of factors known to influence intertemporal preferences. For example, people are more patient when the time of reward outcomes is expressed as an exact date as opposed to the duration of time from the present (Read, Frederick, Orsel, & Rahman, 2005). A recent fMRI study has shown that a similar manipulation, switching from delays to dates, modulates dlPFC activity, consistent with dual system theory (Peters & Büchel, 2010). Perhaps as interestingly, the dual system framework suggests novel effects. The idea for the decimal effect arose from considering ways in which we might modulate NAcc activity.

Positing two neurocognitive systems is almost certainly an oversimplification of how intertemporal preferences are actually constructed. The validity of dual system models of discounting is a source of much debate in the neuroscience literature (e.g., Hare et al., 2009; Kable & Glimcher, 2007). Nonetheless, such models have distinct advantages in accounting for numerous phenomena in delay discounting (van den Bos & McClure, 2013). One important future direction will be to relate dual system models to construal level theory (Trope & Liberman, 2003). Recent work by Fujita and colleagues has shown that priming people to think in broader, more abstract terms (high-level construal) increases self-control (Fujita & Han, 2009). It is intriguing to hypothesize that thinking more abstractly depends on the dlPFC and priming this neural system increases that self-control, but this is pure speculation at this point. We also acknowledge that there may be other plausible mechanisms than the dual processing account or the familiarity of rounded numbers that may explain the downstream effect of an increased affective response to the rounded stimuli studied herein. However, our primary goal for this project was to document the outcome of altered affective responses. Future studies will attempt to determine the mechanism underlying the outcome.

The decimal effect also suggests one avenue for interventions aiming to ameliorate the effects of impulsivity. Our approach represents a novel attempt to shift impulsive behavior in populations associated with poor self-control by manipulating the choice context. ADHD is associated with problematic functioning in brain networks implicated in both cognitive (dlPFC/pPC) and affective/reward (vmPFC/NAcc) processes (Fassbender & Schweitzer, 2006). Despite this, attempts to modify self-control in ADHD and adolescents tend to focus on teaching deliberative strategies (Dawson & Guare, 2010). It should be possible to design choice environments in ways that decrease affective responses, reduce NAcc activity, and lead to more far-sighted choices. This suggestion is very similar to Mischel and colleagues' demonstration that, thinking of the abstract, physical qualities of a marshmallow increase ones' ability to delay gratification and ultimately obtain more marshmallows (Mischel & Baker, 1975). The findings here suggest the neurobiological basis by which these framing effects may function. It may also be that differential neural activity relates to distinct symptom profiles in individuals with ADHD. For example, steeper discounting may be because of some combination of heightened sensitivity to immediate rewards, problems with response inhibition, or an ineffectiveness of future outcomes to influence current behavior.

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