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Valuation of Reward with Long-Term Stimulant Abuse: The Specificity of Decision-Making Biases in Cocaine Addiction But Not Binge Eating Disorder

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Abstract

Background: Previous studies have suggested that cocaine users have higher delay discounting rates than controls when the data is analyzed using a hyperbolic model. However, there is growing evidence indicating that there are two processes in the decision associated with the delay discounting task. The aim of current study was to examine the impact of a two-parameter model in specifying the nature of several decision-making biases in cocaine users.

Methods and findings: The study compared the findings resulting from a hyperbolic model and a saturating-hyperbolic model that specifies two parameters for both a delay discounting and a probability discounting task. Further, cocaine users (n=36) were compared with healthy controls (n=37); and binge eaters (n=20) were compared with non-binge eating controls (n=16) and overweight controls (n=19). The findings from the hyperbolic model replicated the results of previous studies and indicated cocaine users had higher delay discounting rates (z=-3.13, p=.002, d=0.79), but were not different from controls with respect to probability discounting rates (z=-0.68, p=0.50, d=0.16). However, when the data were analyzed with the saturating-hyperbolic function, cocaine users did not have significantly higher delay discounting rates than controls (z=-1.62, p=0.11, d=0.39). Rather, they showed significantly higher saturation indices than controls on both delay discounting task (z=-2.32, p=0.02, d=0.56) and probability discounting task (z=-2.24, p=0.025, d=0.56). This was not observed in binge eaters.

Conclusion: The observed decision-making bias in cocaine users is more associated with the valuation bias of objective rewards than impatience. Chronic cocaine users tend to demand higher rewards to be satisfied. This may be due to acquired reward insensitivity after repeated exposure to cocaine. This effect does not seem to be germane to the acquisition and maintenance of binge eating.

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Introduction

Cocaine addiction is a disorder characterized by repeated self-administration of cocaine despite aversive consequences. Because self-administration is a decision, a great deal of work has focused on the sources of decision-making biases that maintain addictions [1]. A large body of work suggests that the loss of executive, top-down control over behavior is the primary mechanism underlying the decision-making biases in cocaine addiction [2-4]. One of the most valuable tools in documenting these impairments has been the delay discounting task, which measures participants' preference for smaller-sooner rewards compared to larger-later rewards. Because cocaine users generally prefer smaller-sooner rewards compared to controls, this has been interpreted as indicating impatience and impulsivity rather than considered reflection and the ability to represent long-term gains [5]. Underlying this interpretation of the data has been the practice, adapted from economics, of using a single parameter, in this case a hyperbolic, function to summarize participants' preferences and interpreting the parameter narrowly as time preference or a discounting rate and therefore impulsivity [6-8].

However, this approach overlooks another potentially important decision-making bias in cocaine users.

Imaging studies and psychopharmacological studies have highlighted the importance of deficits in reward processing circuits in addiction. While hypersensivity to reward may be a vulnerability to the development of addiction [9], natural reward insensitivity and increased requirements for reward may characterize addiction [10]. Further, the decreased sensitivity can be a response not only to frequent exposure to drugs, but also to monetary rewards [11, 12]. Thus, the dysfunction in reward sensitivity can be vulnerability or a result of reward associated learning [10]. Furthermore, individual differences in reward valuation are known to affect delay discounting curves [13-16]. This work suggests that delay discounting choices reflect not only discounting but also reward sensitivity. The current study is therefore designed to assess the importance of this heretofore neglected influence on decisions made in this paradigm generally interpreted as a measure of impulsivity. The study will also be able to examine convergence with risky decisions without a temporal component, how these parameters relate to addiction severity, and whether these impairments are characteristic of other putative impulsive disorders, such as binge eating disorder.

Deficits in executive controls and hyperbolic model

Impulsivity, and its behavioral correlates (i.e., inattention, behavioral disinhibition, and impulsive decision making), has been conceptualized as a major pathway of developing drug addiction [4, 17-19]. Using hyperbolic model, the delay discounting task has been widely used as an assessment for impulsive decision making, especially in the substance use literature [5]. The hyperbolic discounting function refers to a decrease in discounting rate when the delay is increased [20]. The discounting rate is steep when the delay is relatively short, and it is shallow when the delay is relatively long. This function can be represented by the following formula:

$$V = \frac{A}{(1+kd)}$$

In this classic formula, V refers to the subjective value of a delayed outcome, A represents the objective amount of the delayed outcome, *d* refers to the delay time for the outcome, and *k* represents the delay discounting rate [21]. A higher *k* means there is a steeper discounting function and stronger preference for more immediate and smaller outcome (or greater impulsivity). This model supposes that individuals have the same immediate valuation of the objective reward choices and this value is discounted when processing different delays. This function has been found to fit reasonably well in both human and animal studies [22, 23].

Deficits in reward processing and individual difference in reward valuation

As noted earlier, decreased reward sensitivity is another hypothesized underlying mechanism associated with addiction [10]. The decreased sensitivity is associated with the hypodopaminergic state and decreased valuation of non-drug reinforcers [10, 12, 24]. How individual values a reinforcer may depend on specific reinforcement learning systems, which include Pavlovian association (only assign values to a small set of response), habitual response (assign values to many actions through learning), and goal-directed decision systems that is flexible and open to changes in environment [25]. In this context, previous studies have indicated that habitual learning is important in drug addiction. A Pavlovian association between stimulus and response can become habitual with training over time through the hedonic effect of repeated drug use, impact on neuropharmacological level, and neural circuits [26-28]. This change may also represent the transition between initial drug use and drug addiction [27].

Two decision components and two-parameter models

Animal studies suggested that both genetic vulnerability to behavioral disinhibition and sensitivity to reward related cues are associated with development of addictions [9]. Dopamine receptor activation and valuation bias are also thought to be involved [29]. Given increased evidence about connections between these domains, two parameter models of delay discounting may need to be more nuanced, allowing differentiation between the decision factor associated with valuation of reward (monetary utility) and the factor associated with discounting due to time delay [13-16].

Doya's review [30] of decision making models considered both executive control and valuation biases in describing delay discounting. Specifically, he showed that the valuation of reward or reward utility follows a saturating function which can be used to reflect a decrease of the valuation of the reinforcer due to habitual learning in addition to any impact of differences in discounting. A higher saturation index means a lower subjective value given an objective amount, indicating a higher threshold for feeling satisfied and therefore a higher demand of objective reward. For example, a high grade on a paper would be less rewarding for a strong student compared to an average student because strong students generally are used to and expect to have high grades (i.e., have a higher saturation index for the value of a grade). The equation for the saturating function is listed below, where A is the amount of the objective reward, and Q (saturation index) determines the amount with which the utility curve saturates:

$$f(A) = \frac{A}{A+Q}$$

Further, the saturation index can be combined with a hyperbolic function to incorporate the discounting associated with time delay [30], such that the contributions of discounting and valuation bias to the subjective value (V) can be parsed:

$$V = \frac{A}{(A+Q)} \times \left(\frac{A}{(1+kd)} \right)$$

To differentiate the discounting parameter in this model (*k*) from

the delay discounting rate in the standard hyperbolic model, we will refer the discounting parameter in this model as the "time discounting parameter". It should be noted that this saturating-hyperbolic model is a generalization of the hyperbolic model. It reduces to the hyperbolic model when Q=0. However, when Q>0, the delay discounting curve starts at a value that is lower than the objective reward and produces a shallower curve than the hyperbolic model when the delay is relatively long. Therefore, this saturating-hyperbolic model allows a direct comparison of the sources of individual differences in subjective value.

These theoretical considerations raise the possibility, but do not conclusively show that a simplified, single parameter model could misrepresent a more complicated set of psychological processes. Therefore, we used a simulation method to determine whether a difference in the saturation index could be mistaken for a discounting parameter difference when no discounting difference actually existed. To explore a dramatic but plausible scenario, two samples were randomly assigned k-values from the same distribution derived from pilot data with undergraduate students. The groups were also assigned Q-values from distributions whose means differed by 1 SD (effect size d=-1.0). Indifference points were generated for each simulated subject based on these parameters, and a standard hyperbolic model was fit to the resulting data. The effect size of the calculated group difference in k was 0.60. Thus, a moderately large effect size in k was induced where none existed before simply by fitting the data using the over-simplified one parameter model. Thus the potential of fitting an oversimplified model to the data could have important consequences to our interpretation of the nature of any group differences that are detected.

The uniqueness of valuation or discounting bias in cocaine addiction

Impatience and risk-taking can be operationalized by choice behaviors evident during delay discounting and probability discounting tasks [31, 32]. Some studies suggest a commonality of delay discounting performance and probability discounting performance in gamblers [33] and undergraduate students [34]. However, there is also evidence that smokers showed higher delay discounting rates but not lower probability discounting rates than controls [35]. Given that these studies used a single parameter (i.e., hyperbolic discounting model) to analyze delay discounting performance, the inconsistent results may in part come from an inability to differentiate subcomponents associated with delay discounting and probability discounting. The current study attempted to disentangle the unique aspects of delay discounting associated with decision-making bias in cocaine users by applying a two parameter, saturating-hyperbolic model. Some researchers suggest that the preference of sooner and smaller rewards is a general feature of all impulsive disorders, and that a steep delay discounting rate is a short-hand definition of impulsivity [36, 37]. However, this remains to be demonstrated. One putative impulsive disorder without the involvement of substance use is binge eating disorder (BED), which is characterized by uncontrollable overeating. Literature on BED studies suggests a commonality between BED and cocaine addiction such that both are related to habits and preferences that are learned through the reinforcement of powerful and repetitive rewards [38]. Binge eating disorder is also considered as an impulsive disorder because clinical observations indicated reward sensitivity or drive may play an important role in developing this condition [39]. Further, binge eating disorder and substance use disorder (SUD) co-occur at high rates. For example, Peterson and colleagues [40] studied the mental health history and responses to self-report questionnaires in a sample of female binge eaters. Of the 84 binge eating respondents, 39 (46%) evidenced SUD. The binge eater and SUD group was reported to have more binge eating episodes on the Eating Behavior-IV and higher impulsivity on the Multidimensional Personality Questionnaire (MPQ) than the non-SUD group.

Research on binge eating disorder is less thorough than that on cocaine addiction. Literature on binge eating disorder studies suggests a commonality between binge eating disorder and cocaine addiction such that both are related to habits and preferences that are learned through the reinforcement of powerful and repetitive reward [38]. Binge eaters, however, do not have the adaptation of neurocircuitry due to the drug use.

However, the association between discounting performance and binge eating disorder remains unclear. A recent study failed to detect a group effect among binge eaters, obese women, and normal controls on delay discounting after controlling for education level [41]. However, another study indicated that obese women have significantly lower delay discount AUC (area-under-curve) scores than controls [42]. Thus, one goal of the present study was to compare cocaine users and binge eaters based on their performance on the same decision making tasks to determine whether any decision-making bias found in chronic cocaine users is a general feature of both disorders.

Current study

The aim of current study was to examine the impact of a two-parameter model in specifying the nature of several decision-making biases in cocaine users. To this end, we wanted to systematically compare the associated components at the parameter level (saturation index and discounting index), the task level (delay discounting and probability discounting), and the model level (hyperbolic and saturating-hyperbolic), across disorders (cocaine dependence and binge eating disorder). We anticipated that we would replicate findings from previous studies if we applied a hyperbolic model to our current data. That is, chronic cocaine users would have significantly higher delay discounting rates than controls when analyzed with hyperbolic model. When applying the saturating-hyperbolic model, we expected that cocaine users would have a significantly higher saturation index than controls given that higher saturation index indicates a valuation bias reflecting reduced reward sensitivity, perhaps due to habitual learning processes. Further, we also assumed that cocaine users may still have higher delay discounting rates than controls after accounting for the valuation bias given that impatience has been considered an important underlying mechanism of cocaine addiction. In addition, we anticipated that cocaine users would have lower probability discounting rates than controls because a low probability discounting rate indicates a tendency to risk taking, an important construct that has been

associated with some impulsive disorders. To the extent that both disorders are associated with impulsivity, we hypothesized that binge eaters would also share these features.

Method

Participants

Participants were recruited through postings and newspaper advertisements. All participants were told that they would be paid 180 dollars for completing all three sessions. The final samples included 36 active cocaine users, 37 matched healthy, non-cocaine using controls, 20 female adults with binge eating disorder, 16 normal, non-binge eating female controls, and 19 overweight non-binge eating female controls. To rule out the association between weight and decision-making bias, both normal controls and overweight controls were included, and their responses were compared to those of the binge eaters. All participants were between age 18 and 46 years.

For the cocaine users, inclusion criteria were: 1) meeting *DSM-IV* (4th ed.) diagnostic criteria for cocaine dependence for at least 1 year; 2) meeting that criterion within the month prior to enrollment in the study; and 3) having used cocaine at least 6 times in the month prior to enrollment in the study. Exclusion criteria were: 1) a prior history of neurological illness, bipolar, or psychosis, 2) depressive disorder in the last month, 3) HIV sero-positivity; 4) current medication that may alter gamma-aminobutyric acid brain levels (a criterion related to a different assessment procedure); 5) current alcohol use >10 drinks/week for women and 12 for men; and 6) current dependence on any psychoactive substance (with the exception of cocaine, caffeine, or nicotine). For the binge eater group, only female participants were enrolled. The inclusion criterion was meeting *DSM-5 proposed* diagnostic criteria for binge eating disorder. Exclusion criteria were: 1) no substance use disorders over the previous six months; 2) no bulimia nervosa and cocaine exclusionary criteria as listed above. For healthy controls, exclusion criteria were: 1) any diagnosed psychiatric disorder in the past 3 months prior to enrollment; and 2) a history of substance dependence or substance abuse within the past year (with the exception of caffeine or nicotine). These control participants were matched with either active cocaine users or binge eaters on demographic variables listed in **Table 1** (**Supplementary Tables 1 and 2** provide further detail about participants' parents' education levels).

Measures and Procedures

Discounting measures [43]

The delay discounting task measured subjective values after certain, hypothetical delays. The current version was a computerized random adjusting-amount procedure in which the smaller and immediate reward was adjusted until the value of the small reward was equal to the subjective value of the large and delayed reward (which indicated that an indifference point was reached). The task allowed participants to choose from $10 after a delay (1, 2, 30, 180, or 365 days) or an immediate and smaller reward. For example, participants were offered the following choice: Would you rather have $5 now or $10 in 30 days? After the participant made a choice, the answer was used by the program to narrow the range of the immediate rewards for the subsequent questions. A series of alternatives was presented until an indifference point at a certain delay time was reached. In addition, the adjusting nature of the task was masked by mixing the delay discounting questions and probability discounting questions. Because there were 5 delay times, completing the task would lead to 5 indifference points which yielded a delay discounting curve. A steeper delay discounting curve indicated a stronger preference for more immediate and smaller rewards.

The probability discounting task measured the subjective values with certain probability against receiving the reward. In the task, participants were asked to choose from $10 with a probability (95%, 90%, 75%, 50% and 25%) and a smaller, guaranteed amount of money. For example, one of the questions was "Would you rather take $5 for sure or $10 with a 50% chance?" Again, the smaller and assured reward was adjusted until an indifference point was reached for each probability level. The adjusted procedure was masked by mixing the probability questions with the delay questions. The 5 indifference points generated from the 5 probability levels were used to generate a probability discounting curve. A steeper probability discounting curve meant a stronger preference for more certain and smaller rewards (or higher risk aversion).

Participants completed the study in three sessions, with the third session consisting of an MRI scan, which is not discussed further. During the first session, participants underwent informed consent and a clinical interview to assess whether or not they met certain *DSM-IV* criteria using a Structured Clinical Interview for Axis I disorders. The cocaine users also completed a cocaine craving questionnaire [44], brief substance craving questionnaire (Somoza et al.), and eating disorders examination questionnaire (EDE, Fairburn). Binge eaters and controls for both groups also completed the EDE and Stunkard-Messick Eating Questionnaire (SMEQ, Stunkard and Messick). During the second session, all participants completed the discounting tasks as part of a broader battery of computer-administered cognitive tasks counter-balanced across participant.

Data analysis

Data check: The final samples were determined after a data check based on an algorithm developed by Johnson and Bickel [45]: 1) an indifference point was greater than the preceding point for more than 20% of the largest delayed reward; 2) the last indifference point was not less than the first indifference point for at least 10% of the largest delayed reward. We modified the second criteria to no discounting at all given that our longest delay was shorter than that in Johnson & Bickel [45]. Nonsystematic discounting data from 3 cocaine users, 3 cocaine controls, 3 binge eaters, 3 normal binge eater controls, and 4 overweight binge eater controls were excluded from further analysis. Follow-up analyses consisting of a t-test, one-way analysis of variance (ANOVA) and χ^2 and summarized on **Table 1** showed there were no significant differences on the demographic variables between the clinical groups and their matched control groups.

Calculation of discounting: When fitting discounting data, the first

Table 1 Demographics for cocaine-dependent participants (CD), CD Controls, Participants with binge eating disorder (BED), BED overweight controls, and BED normal controls.

Characteristic	Group				
	CDs	CD Controls	BEDs	BED Normal Controls	BED Overweight Controls
n	36	37	20	16	19
Age	38.81 (7.25)	38.79 (7.12)	33.50 (8.22)	31.44 (7.65)	32.74 (7.55)
Gender (% female)	18.91	23.07	100	100	100
Race (% Caucasian)	36.1	76.9	72.7	81.2	89.5
Education (in years)	13.14 (1.82)	14.59 (1.52)	15.60 (1.82)	15.19 (1.76)	14.89 (2.19)
Mother's Education level	2.46 (1.77)	2.85 (1.50)	3.00 (1.21)	3.44 (2.06)	2.89 (1.28)
Father's Education level	2.83 (2.06)	3.26 (1.76)	3.20 (2.02)	3.63 (2.39)	3.22 (2.07)
Years of use (cocaine)	14.53 (7.48)	--	--	--	--
Days of use (per week)	3.42 (1.68)	--	--	--	--
BMI	--	--	34.64 (3.68)	23.10 (1.87)	34.27 (4.47)

Note: BMI refers to Body Mass Index, a measure of body fat based on height and weight. A BMI of 30 or higher is considered as overweight. Parents' Education Levels were rated with a Likert scale in which 1=8th Grade, 2=12th Grade, 3=Associate's degree, 4=Bachelor's degree, 5=Professional degree, 6=Master's degree, and 7=Doctorate.

step was to generate the indifference points at which the subject had equal chances of selecting either of a pair of alternatives (e.g., $5 now or $10 in 30 days). These indifference points form a series of delay or probability choices that were used to form a discount curve from which parameter estimates could be extracted. The delay and probability discounting parameters were first analyzed using a hyperbolic function to replicate the results from previous studies and then were analyzed using a saturating-hyperbolic function to test the hypotheses of the current study.

Comparison of model fitting: The relative goodness-of-fit was evaluated using sums of individual Akaike Information Criterion (AIC) scores. There were different numbers of parameters (thus different numbers of degree of freedom) involved in these models. Thus, AIC was used because it is a method for guiding model selection that penalizes on number of parameters [46, 47]. The sum of individual AIC scores had been used as the primary index for model comparison [48]. In addition, paired wise t tests were conducted to compare individual AIC scores for each group to provide additional evidence for the robustness of the model superiority.

Group differences and correlations: Indifference points at each scale of discounting tasks were first compared to provide some evidence for group difference without applying the model fitting. The t tests with bootstrap resampling were used to compare group means of indifference point at each delay time (1, 2, 30, 180 and 365) and each probability scale (95%, 90%, 75%, 50% and 25%). This method was appropriate in this context to avoid parametric assumptions. Because non-independent tests were performed, type I error rate was set at 0.01. After applying the hyperbolic model or saturating-hyperbolic model, the nonparametric tests (the Mann-Whitney U test or the Kruskal-Wallis test) were used to detect group differences on discounting parameters given that the distribution of discounting parameters were nonparametric. Unfortunately, the nature of the data precluded tests of group by parameter interactions [49]. Further, a Mann-Whitney U test was used to detect differences on parameters between the severe users (n=17, use cocaine more than 3 days per week) and less severe users (n=18, use cocaine equal or less than 3 days a week) within the cocaine group. To avoid parametric assumptions, Spearman correlations were calculated to test the correlations between parameters. To compare the correlation coefficients, Pearson correlation coefficients were calculated based on the Spearman correlation coefficients, and the differences were tested using Fisher's Z-transformation according to Myers and Sirois [50].

Results

Model fitting

The saturating-hyperbolic model appeared to be a better fit than the hyperbolic model in both cocaine group and control group. The sum of individual AIC scores in cocaine group was 506.50 for the saturating-hyperbolic model, in comparison to 626.57 for the hyperbolic model. In addition, the pairwise t-test result indicated that the individual AIC scores for the saturating-hyperbolic model were significantly lower than the individual AIC scores for the hyperbolic model ($t=3.78$, $df=35$, $p=0.001$). (To evaluate whether this was criterion specific, we calculated and observed a largely identical result when comparing BIC, or Bayesian Information Criterion, scores, $t=4.2$, $df=35$, $p<0.001$). Similarly, the sum of individual AIC scores in the control group was 423.19 for the saturating-hyperbolic model and 455.44 for the hyperbolic model, although the paired wise t test on individual AIC scores for these two models was not significant ($t=1.18$, $t=36$, $p=0.24$).

Group effect on indifference points and discounting parameters for cocaine users versus controls

As shown in **Table 2**, the cocaine group showed significantly lower indifference points at day 1, 2, 30, 180, but not at day 365. The cocaine group also showed significantly lower indifference points at probability of 95%, but not at probability scale of 90%, 75%, 50% and 25%.

When analyzed with the hyperbolic model, results of Mann-Whitney U tests showed that the cocaine users had higher delay discounting rates than matched controls ($z=-3.13$, $p=0.002$,

Table 2 T-test results of indifference points (cocaine vs. controls) at each time scale.

Delay (days)	Cocaine M(SD)	Control M(SD)	Group difference (cocaine-control)	t	p value*	Effect size (Cohen's *d*)
Delay Discounting						
1	8.19 (2.34)	9.71 (.51)	-1.522	-3.811	<0.001	-.90
2	7.61 (2.31)	9.38 (1.10)	-1.767	-4.160	<0.001	-.98
30	4.39 (2.83)	6.76 (3.04)	-2.368	-3.445	<0.001	-.81
180	2.57 (2.30)	5.03 (3.37)	-2.458	-3.643	0.001	-.85
365	1.99 (1.91)	3.57 (3.28)	-1.581	-2.526	0.014	-.59
Probability Discounting						
95%	7.49 (2.77)	8.83 (1.33)	-1.352	-2.644	0.009	-.57
90%	7.06 (2.85)	8.15 (1.86)	-1.093	-1.936	0.054	-.24
75%	5.72 (2.92)	5.86 (2.10)	-0.143	-0.239	0.805	-.06
50%	4.11 (2.59)	3.33 (1.90)	0.381	0.715	0.453	.34
25%	2.29 (1.98)	1.99 (1.07)	0.305	0.815	0.420	.19

Note: The indifference point refers to the point at which the subject has equal chances of selecting either of a pair of alternatives; p-values ascertained using a bootstrap method.

d=0.79). However, there was no significant group difference between cocaine users and matched controls on the probability discounting rates (z=-0.68, *p*=0.50, d=0.16).

When analyzed with the saturating-hyperbolic model, the cocaine users had higher saturation index than the controls (z=-2.32, *p*=0.02, d=0.56) on the delay discounting task, but not the time discounting index (z=-1.62, *p*=0.11, d=0.39). That is, the time discounting effect size from the saturating hyperbolic model was approximately 50% smaller than with the single parameter model. Consistent with these observations, cocaine users also had a higher saturation index than the controls on the probability discounting task (z=-2.24, *p*=0.025, d=0.56). This appeared as a trend for the probability discounting index (z=-1.89, *p*=0.06, d=0.46).

To illustrate the group difference on delay discounting parameters, mean indifference points and confidence intervals were calculated with bootstrap resampling at each time scale and were fit with hyperbolic and saturating-hyperbolic models.

As shown in **Figure 1**, the cocaine group showed steeper discounting on decisions associated with delay rewards when the data was analyzed with the hyperbolic model (top left), but not on decisions associated with probabilistic rewards (bottom left). However, when the data was analyzed with the saturating-hyperbolic model, the cocaine group showed a consistently lower start point of discounting than the controls for decisions associated with delay rewards (top right) while the actual slopes of the curves were not too dissimilar. The cocaine group also showed a lower start point of discounting than the controls for decisions associated with probability rewards (bottom right), but the curve was slightly flatter than for the controls. This commonality across tasks suggested the observed decision bias in cocaine addicts is more strongly associated with the decision factor related to immediate valuation bias of the reward rather than the discounting effect.

Regarding the parameter difference between the severe users and less severe users in cocaine group, there were no differences in delay discounting rate (z=-0.41, *p*=0.68, d=0.12) from the hyperbolic model. Where using the saturating-hyperbolic model, there was no difference in the time discounting parameter (z=-1.23, *p*=0.22, d =0.43) but there was a significantly higher saturation index in more severe users than in less severe users in the predicted direction (z=-2.27, *p*=0.02, d=0.83).

Correlations between parameters

For controls and cocaine users, the delay discounting rate from the hyperbolic model was highly correlated with the time discounting parameter from the saturating-hyperbolic model (ρ=0.83, p<0.001), although this rate was significantly greater for the controls relative to the cocaine users (ρ=0.98 vs. ρ=0.57, respectively, z=7.2, p<0.001). The correlation between the delay discounting rate from the hyperbolic model and the saturation index was not significant (ρ=0.06, p=0.59), whereas between time discounting and saturation indices from the saturating-hyperbolic model were negatively correlated (ρ=-0.43, p<0.001) such that the more one devalued the reward at the outset, the less likely he or she was to discount the value of that reward over time. Group status did not significantly affect these latter correlations.

When examining the association between the delay discounting paradigm and probability discounting paradigm using saturating-hyperbolic model, the time discounting parameter was somewhat correlated with probability discounting parameter (ρ=0.19, p=0.03) and were similar across groups. The saturation index from delay discounting task was also significantly correlated with the saturation index from probability discounting task (ρ=0.33, p<0.001), with a nearly significantly higher correlation in controls than in cocaine users (ρ=0.48 vs. ρ=0.06, respectively, z=1.96, p=0.05).

Group effect on discounting rates for binge eaters versus controls

Results of Kruskal Wallis Tests indicated that binge eaters did not show significantly higher or lower discounting parameters than either normal weight controls or over-weight controls when using either the hyperbolic or the saturated hyperbolic models. The significant level ranged from 0.15 to 0.98. Mann-Whitney U

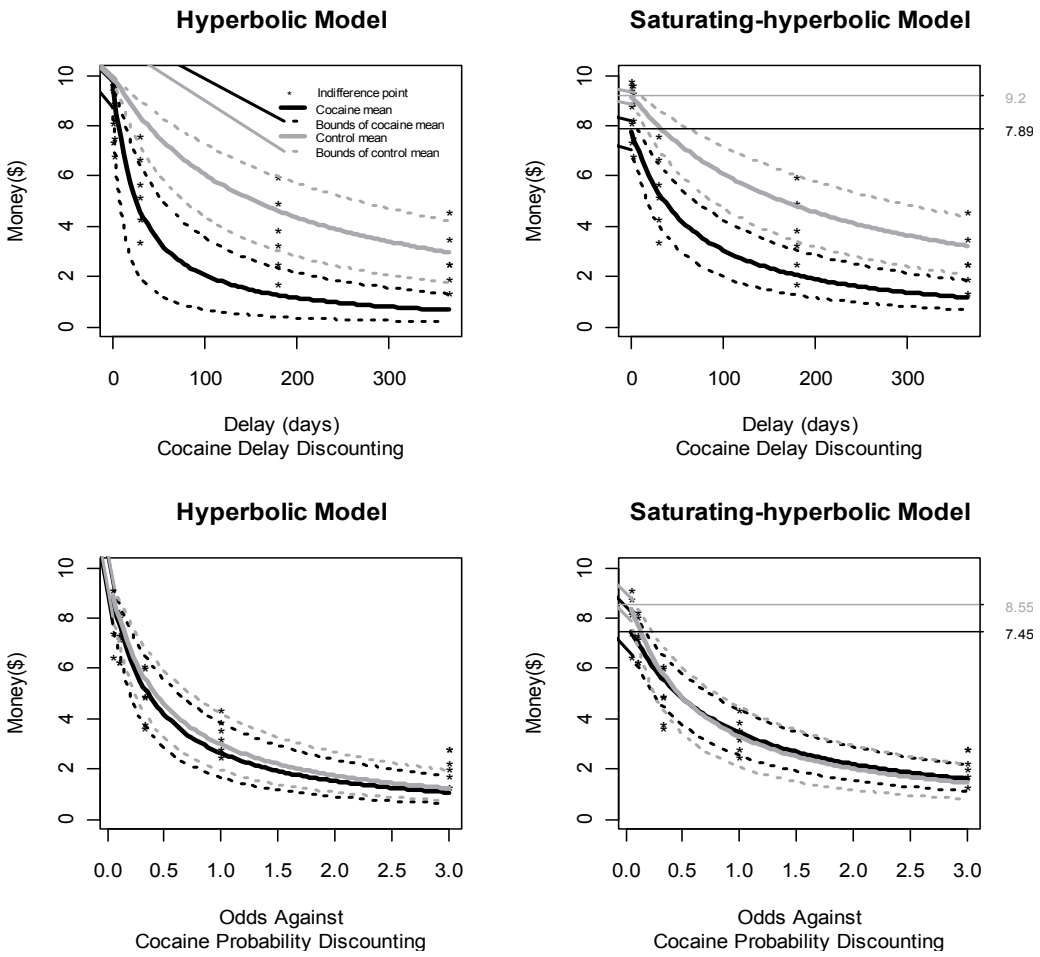

Figure 1 Mean (and confidence intervals) of discounting curves in cocaine users. The top set of graphs shows the mean delay discounting curves and confidence intervals in cocaine users (n=36) and matched controls (n=37). Top left figure shows the means (solid lines) and confidence intervals (dotted lines) for delay discounting curves in cocaine users and controls when the data is analyzed with hyperbolic model. Top right figure shows mean delay discounting curves and confidence intervals for cocaine users and controls when the data is analyzed with saturating-hyperbolic model. The bottom set of graphs shows mean probability discounting curves and confidence intervals. Details are the same as in the top set of graphs.

test for the group difference between binge eaters and normal controls also yield non-significant results with significant level ranged from 0.28-0.97. The effect sizes (d) ranged from 0.37 (delay discounting saturation) to 0.02 (probability discounting). As shown in **Figure 2**, the discounting curves of the three groups overlapped.

Conclusion and Discussion

The present study examined the specificity of decision-making bias in cocaine dependence when the discounting data were analyzed using both the standard hyperbolic function and saturating-hyperbolic model. When applying the hyperbolic function, current results replicated findings from previous studies that cocaine users had significantly higher delay discounting rates than controls. In addition, cocaine users did not show lower probability discounting rates than controls. However, when the data was examined using the saturating-hyperbolic function, which contained an additional parameter to fit, the cocaine users showed markedly more normal delay discounting rates that were no longer reliably different from controls. Instead, cocaine users showed significantly higher saturation indices on both the delay and probability discounting tasks. In contrast to cocaine users, the binge eaters did not show significant differences from either the normal controls or over-weight controls on any discounting parameters.

The findings from the hyperbolic model have replicated the results of previous studies, indicating that cocaine users have higher delay discounting rates than controls [7, 8, 51]. Based on these results, one is led to believe the decision-making bias observed in cocaine users is specific to the difficulty with executive functions (i.e., impatience). However, findings from saturating-hyperbolic model challenge this interpretation, and highlight the importance of a decrease of valuation of rewards (high saturation index) in the decision-making bias. With regard to the statistical power, the current study included a total of 73 cocaine users and

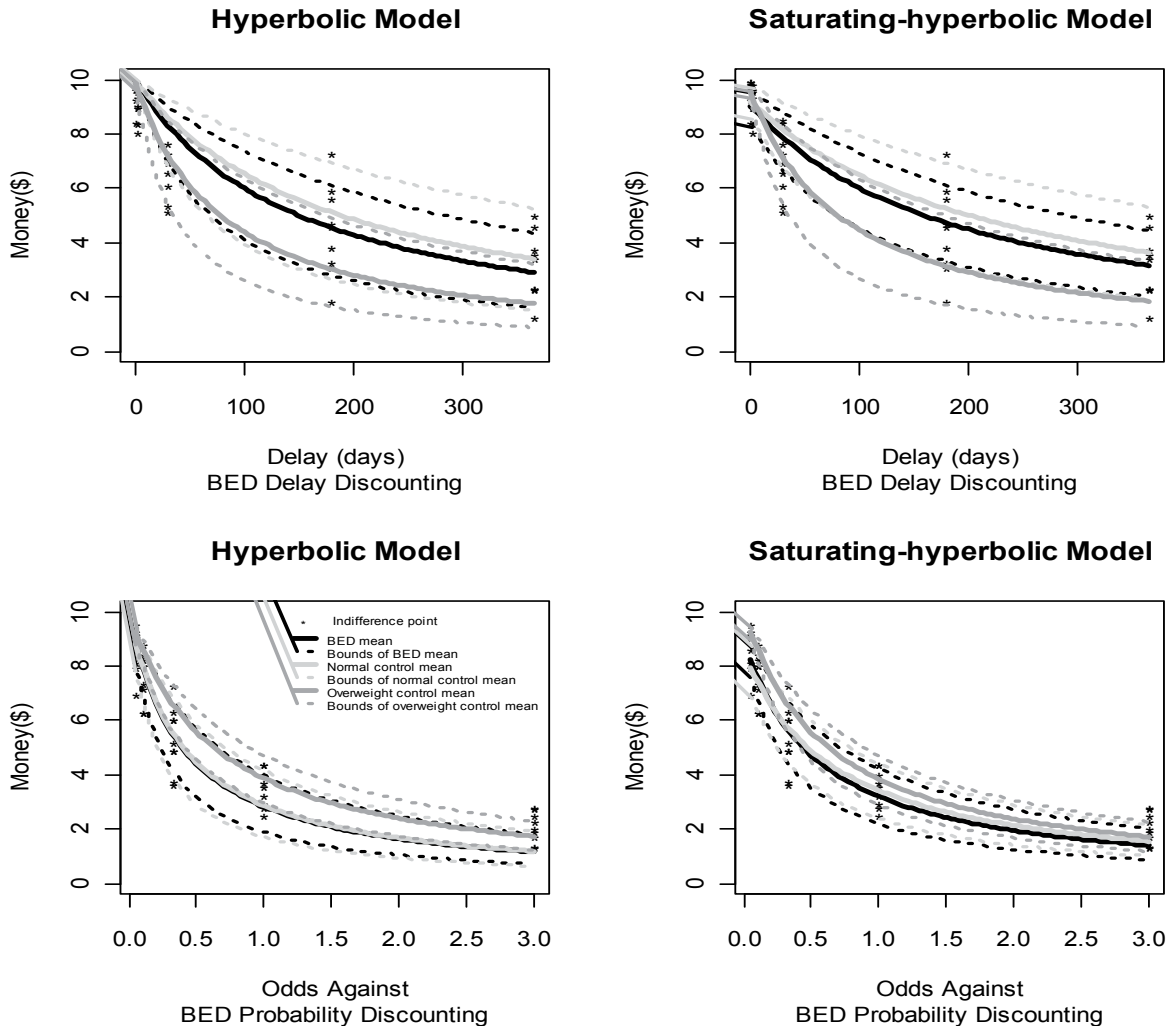

Figure 2 Mean (and confidence intervals) of discounting curves in binge eaters. The top set of graphs shows the mean delay discounting curves and confidence intervals in binge eaters (n=20), normal-weight controls (n=16), and over-weight controls (n=19). Top left figure shows the means (solid lines) and confidence intervals (dotted lines) for delay discounting curves in three groups when the data is analyzed with hyperbolic model. Top right figure shows mean delay discounting curves and confidence intervals for binge eaters and controls when the data is analyzed with saturating-hyperbolic model. The bottom set of graphs shows mean probability discounting curves and confidence intervals for these groups. Details are the same as in the top set of graphs.

controls, thus making our power to detect effects comparable to that of other important experimental studies in this area (e.g., Heil, Johnson, Higgins & Bickel; 63 cocaine users and controls). In the event, the effect size derived from the k parameter in the saturating hyperbolic model was .39, which would general require 160 subjects to obtain power of 0.80 (assuming α=0.05 and a parametric distribution).

The hyperbolic model is a special case of the saturating-hyperbolic model and assumes that each participant has the same saturation index equal to zero. While this assumption may generally be appropriate in normal population, it was not appropriate for this cocaine group. Results of the current study indicated that the saturation indices were close to zero for the majority of controls, but it was higher and much more variable in the cocaine group. These findings point to the importance of examining individual differences using the saturation index.

Although perhaps less germane in models of decision-making in controls, the addition of models with a saturation index may be particularly important when describing cocaine users. Results of the current study showed that the time discounting parameter in cocaine users was only moderately correlated with the delay discounting rate from the hyperbolic model, although this correlation was close to 1 in the control group. This may indicate that although the time discounting parameter could be explained by the delay discounting rate in a normal population, this assumption does not apply to chronic cocaine users. Our data further showed that one can be led to very different conclusions depending on whether one assumes that the saturation index reflects no individual differences relevant to delay discounting decisions in chronic cocaine users.

The finding of a valuation bias of nearly the same magnitude in cocaine users in both the delay and probability discounting tasks suggests that chronic cocaine users may require greater rewards

to feel the same level of satisfaction. This was also the only index that differentiated the severe use group from the less severe use group. Thus, the frequency of drug use appeared to be associated with a stronger valuation bias and therefore a higher threshold to be satisfied. This may be associated with the dysfunction of dopaminergic system. In the literature of drug addiction, the dopaminergic system has been found to play an important role in evaluating choices through trial and error learning process [28, 52]. Previous studies suggested that dopamine levels in drug users showed an increase in the initial phase of drug use and then a decrease with repeated exposure to drugs [53-55]. Reward encoding is based on the magnitude and unpredictability of rewards [56]. With repeated exposure to addictive drugs and the decrease of unpredictability of rewards, drug users may need a higher level of rewards to maintain a stable dopamine level. This change has been considered as a homeostatic regulation [56, 57]. This process also highlights the importance of habitual decision making and a decrease of goal-directed decision making in chronic cocaine users. There is evidence suggesting that long-term cocaine users show increased behavioral rigidity and compulsive drug consumption which is associated with loss of gray matter in the orbitofrontal cortex [58], a region previously identified as one of the regions associated with "β" parameter that represents "the special value placed on immediate rewards" [15]. The cocaine users in current study have an average use of cocaine for about 15 years. At this stage, the decision-making bias appears to be more associated with valuation bias.

Furthermore, these findings provide some evidence for the commonality of delay discounting and probability discounting. Theoretically, these two tasks share some commonalities, which include a similar conceptual framework and mathematical function [20]. Correlational studies indicate the delay discounting rate and probability discounting rate are either not significantly correlated [59, 60] or they are significantly and positively correlated [61, 62]. Neuroimaging studies suggest there is a common neural system (Ventral striatum and orbitofrontal cortex) that encodes monetary utility for decisions associated with both delayed rewards and probability rewards [16]. This neural system is consistent with the subject specific evaluation system. However, there is also evidence that delay discounting and probability discounting involve at least some distinct processes. There are opposite magnitude effects on delay discounting and probability discounting in that a smaller reward magnitude leads to steeper delay discounting rate and shallower probability discounting rate [63-65]. Factor analyses indicate that delay discounting and probability discounting load on different factors [62]. Current findings suggest there are common and distinct factors involved in delay discounting and probability discounting.

Another finding from this study was that the cocaine users did not share the decision biases with binge eaters, consistent with other results [41]. There is evidence indicating dopaminergic dysfunction also plays a role in eating disorders [38, 66]. However, there appear to be different mechanisms associated with the dopamine involvement in drug users and binge eaters [67]. While Wang et al. endorsed the importance of habitual learning in drug addiction; their study indicated that binge eating is more associated with reward sensitivity to food specifically. Further, discounting for food has been found to be associated with body fat in normal population. Thus, it is also possible that binge eaters only have valuation bias or problems with executive controls associated with food, which remains to be studied.

This study has several limitations. First, although participants were selected using stringent inclusion and exclusion criteria, the statuses of cocaine dependence, binge eating disorder, and healthy controls were based on self-report information. Further, the cocaine users reportedly had an average of about 15 years of cocaine use. Some results from the present research may not be generalizable to cocaine users with a shorter use history, nor was it possible to distinguish the risk factors for cocaine use from the sequelae of habitual use. Finally, the sample sizes of participants with binge eating disorder, over-weight controls, and normal-weight controls were relatively small, and only female participants were involved, although the female subgroup in cocaine users did show a trend of group difference from normal controls. Further studies with larger and more heterogeneous samples are needed to replicate the findings from this study.

In summary, the current study expands the research of decision-making bias in cocaine users by applying a novel model that differentiates the monetary utility and time utility. The results indicate that the decision-making bias in long-term cocaine users is more associated with the deficit of reward evaluation system than the impatience or a sense of urgency. The valuation bias is likely associated with habitual learning and neuro-adaptation in dopamine functioning. Our study further supports the treatment that aims to increase the dopaminergic function in chronic cocaine users [55]. Future studies may focus on the impact of this evaluation bias on the intervention efficacy. Treatments that focus on modifying the factors associated with valuation bias may be particularly useful for the most severe users. In addition, binge eating disorder does not appear to share this feature with cocaine dependence, suggesting different underlying mechanisms associated with decisions in binge eaters.

Authors' Note

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