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An Efficient Operant Choice Procedure for Assessing Delay Discounting in Humans: Initial Validation in Cocaine-Dependent and Control Individuals

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Abstract

Delay discounting is the decline in a consequence's control of behavior as a function of its delay, and may be a fundamental behavioral process in drug dependence. Human delay-discounting studies have usually relied on choices between hypothetical rewards. Some human tasks have assessed delay discounting using operant procedures with consequences provided during the task, as in nonhuman animal studies. However, these tasks have limitations such as long duration, potentially indeterminate data, or confounding the effect of delay with probability. A study in 20 cocaine-dependent volunteers and 20 demographically matched non-cocaine-dependent volunteers was designed to investigate a novel operant delay-discounting task providing monetary reinforcement by coin delivery throughout the task (Quick Discounting Operant Task; QDOT). Participants completed a hypothetical delay-discounting procedure, a potentially real reward delay-discounting procedure, and an existing operant delay-discounting task: the Experiential Discounting Task (EDT). The QDOT resulted in complete data for all participants, showed systematic effects of delay that were well described by a hyperbolic function, had a maximum duration of 17 min, and resulted in relatively little variability in session earnings. QDOT performance was significantly, positively correlated with performance on the EDT but not the other tasks. The QDOT resulted in an effect size between the groups that was similar to most other delay discounting tasks examined, and showed the cocaine-dependent participants to delay discount significantly more than the control participants. The QDOT is an efficient operant human delay-discounting task that may be useful in a variety of experimental settings.

Keywords

delay discounting; cocaine; real; hypothetical; human

Delay discounting (also referred to as “time” or “temporal” discounting) refers to the observation that delaying a consequence decreases its effect on behavior. Such devaluation of delayed consequences has been demonstrated in both human and nonhuman animals, typically with choice procedures revealing that, all else being equal, sooner rewards are preferred over delayed ones, and delayed losses or punishments are preferred over sooner ones (Ainslie, 1975; Benzion, Rapoport, & Yagil, 1989; Chung & Herrnstein, 1967; Deluty, 1978; Rachlin & Green, 1972; Rachlin, Raineri, & Cross, 1991; Shelley, 1993).

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Preference for smaller sooner over larger later rewards (i.e., greater discounting) in delay-discounting studies has been associated with numerous behavioral health problems, including drug abuse and dependence (Bradford, 2010; Reynolds, 2006b). In drug abuse/dependence, delay discounting may model the choice between the smaller sooner reward of immediate but short-lived drug effects versus the delayed but (arguably) more valuable improvements in health and social functioning that come with sustained abstinence. The finding that drug abusing/dependent individuals prefer smaller sooner money over larger later money relative to non-drug abusing participants has been shown for tobacco (Baker, Johnson, & Bickel, 2003; Bickel, Odum, & Madden, 1999; Heyman & Gibb, 2006; Johnson, Bickel, & Baker, 2007; Mitchell, 1999; Ohmura, Takahashi, & Kitamura, 2005; Reynolds, Richards, Horn, & Karraker, 2004; Reynolds, 2006a), opioids (Kirby, Petry, & Bickel, 1999; Kirby & Petry, 2004; Madden, Petry, Badger, & Bickel, 1997), alcohol (Field, Christiansen, Cole, & Goudie, 2007; Petry, 2001; Vuchinich & Simpson, 1998), methamphetamine (Hoffman et al., 2006; Monterosso et al., 2007), and cocaine (Coffey, Gudleski, Saladin, & Brady, 2003; Heil, Johnson, Higgins, & Bickel, 2006; Kirby & Petry, 2004), although marijuana may be an exception or associated with a smaller effect size (Johnson et al., 2010). Moreover, preference for larger later rewards is associated with success in drug dependence treatment (Dallery & Raiff, 2007; Krishnan-Sarin et al., 2007; Washio et al., 2011; Yoon et al., 2007). Studies in rats suggest that preference for smaller sooner rewards is associated with vulnerability to acquisition of cocaine self-administration (Perry, Larson, German, Madden, & Carroll, 2005), greater nicotine-seeking during nicotine extinction, and greater reinstatement of nicotine-seeking by re-exposure to nicotine-associated cues (Diergaarde et al., 2008). Finally, studies in rats show that chronic exposure to cocaine (Dandy & Gatch, 2009; A. W. Logue et al., 1992; Mendez et al., 2010; Roesch, Takahashi, Gugs, Bissonette, & Schoenbaum, 2007; Setlow, Mendez, Mitchell, & Simon, 2009; Simon, Mendez, & Setlow, 2007) and amphetamine (Gipson & Bardo, 2009) causes a persistent preference for smaller sooner reinforcers under non-drug conditions. Therefore, delay discounting appears to be important along multiple dimensions for understanding cocaine and other forms of drug dependence.

Some human delay-discounting studies have utilized what this manuscript will refer to as “potentially real reward” procedures. Although potentially real reward methods provide actual consequences, those consequences are all delivered after the task is completed, as opposed to after each trial as in non-human animal delay-discounting studies, and only the consequence for one (or a few) randomly-selected choice trial is provided. Although purely hypothetical procedures have been shown in most circumstances to provide good correspondence to potentially real reward procedures (Baker et al., 2003; Bickel, Pitcock, Yi, & Angtuaco, 2009; Johnson & Bickel, 2002; Johnson et al., 2007; Lawyer, Schoepflin, Green, & Jenks, 2011; Madden, Begotka, Raiff, & Kastern, 2003; Madden et al., 2004) (c.f., Hinvest & Anderson, 2010; Paloyelis, Asherson, Mehta, Faraone, & Kuntsi, 2010), there is nonetheless concern that potentially real reward procedures may assess different behavioral processes than operant procedures such as those used in nonhuman animals. For example, a human operant delay-discounting task, but not a potentially real reward delay-discounting task, showed increased delay discounting after ethanol administration (Reynolds, Richards, & de Wit, 2006). Similarly, the same operant task, but not a hypothetical delay-discounting task, showed decreased delay discounting after methylphenidate administration in children with attention-deficit/hyperactivity disorder (ADHD) (Shiels et al., 2009), suggesting that operant tasks may be more sensitive to drug administration effects than hypothetical or potentially real reward tasks.

A few human operant delay-discounting procedures have been developed using monetary reinforcement (Lagorio & Madden, 2005; Lane, Cherek, Pietras, & Tcheremissine, 2003; Reynolds & Schiffbauer, 2004; Scheres et al., 2006). Although one of these procedures did

not provide reinforcement on some delay trials (Reynolds & Schiffbauer, 2004), and another procedure assessed subsequent choices before some previous choice delays had elapsed (Lagorio & Madden, 2005), all were considered operant procedures because at least some delayed consequences were experienced before subsequent choices were made during the procedure. Although these tasks have been fruitful in addressing a variety of scientific questions, certain aspects of their design may limit their use in some human studies. First, one of these procedures involves probabilistically rewarding a certain proportion of trials, which may potentially confound delay discounting with probability discounting (i.e., the effect of uncertainty on a consequences control over behavior) (Reynolds & Schiffbauer, 2004). Second, some of these procedures involve substantial variability in task duration (e.g., 15 to 50 min) (Lane et al., 2003; Reynolds & Schiffbauer, 2004) or multiple session days (Lagorio & Madden, 2005), which might hamper their use in research relative to hypothetical delay-discounting measures which typically require a single session of less than 10 min. Third, some procedures result in relatively variable and potentially large (e.g., up to \$40 or more) monetary earnings that might constrain their use in some studies (Lane et al., 2003; Reynolds & Schiffbauer, 2004). Fourth, some procedures allow for the potential determination of multiple indifference points rather than a single indifference point at a delay (Lagorio & Madden, 2005; Lane et al., 2003; Scheres et al., 2006), or otherwise indeterminate indifference point(s) (Reynolds & Schiffbauer, 2004), which may result in the need for independent raters to subjectively judge indifference points from the raw data, e.g. (Scheres et al., 2006) (an indifference point is a smaller sooner reward magnitude found to be valued approximately equally with the larger later reward).

The Quick Discounting Operant Task (QDOT) was developed as an operant choice procedure that would require a relatively short time to determine a discounting function (less than 20 min), result in unambiguous determination of a single indifference point at each delay, and involve consequence delivery on 100% of trials. Because delay discounting has been so widely studied in drug-dependent and non-drug-using controls in regard to drug dependence, this study tested the QDOT in cocaine-dependent individuals and demographically matched controls who reported never having used cocaine. In addition to the QDOT, participants completed three previously studied delay-discounting procedures: a hypothetical \$1,000 discounting task (Johnson & Bickel, 2002), a potentially real \$10 discounting task (Johnson & Bickel, 2002), and a previously characterized human operant delay-discounting procedure: the Experiential Discounting Task (EDT) (Reynolds & Schiffbauer, 2004). The primary goals of this study were: 1) to assess the orderliness of QDOT indifference point data in these two relevant populations; 2) compare the four discounting procedures on measures of logistical importance to future study design (frequency of incomplete data sets, study earnings, task duration); 3) examine correlations among these four delay-discounting tasks; and 4) determine the sensitivity of the QDOT to between-subject effects by comparing the effects size between the control and cocaine groups obtained with the four delay-discounting tasks. The study also tested if delay discounting was statistically greater in cocaine-dependent than control participants on the four tasks, although this was not a primary goal of the study because this has been shown regarding cocaine abusing/dependent individuals with hypothetical tasks (Coffey et al., 2003; Heil et al., 2006) and a potentially real reward task (Kirby & Petry, 2004), and because resources constrained the sample to a relatively small size.

Method

Participants

Participants were 40 volunteers, 20 of which were cocaine dependent (cocaine group) and 20 of which were not cocaine dependent (control group). Women comprised 42.5% of the total sample (45% in the cocaine group; 40% in the control group). Participants were

recruited through local advertisements on flyers and in newspapers. Advertisements for the cocaine group requested healthy men and women aged 18-55 years who use cocaine on a regular basis for a non-therapeutic research study about decision making. Advertisements for the control group were identical with the exception that cocaine was not mentioned. Compensation, which was specified in the advertisements, was \$75 for completing a single session lasting approximately 3 hours. Although participants could earn additional money based on task performance, this information was not provided in advertisements or during screening. All money was provided as cash. An initial phone interview was conducted to assess self-reported demographics, psychiatric history, and drug use. Those meeting initial eligibility criteria were invited for further screening in the laboratory. After signing written informed consent at the laboratory visit, participants provided a urine sample for detecting drugs of abuse including cocaine (urine test model DOA-6, Medimpex United Inc., Bensalem, PA), answered more detailed questions regarding topics covered on the phone screen, and completed the Quick Test, a test of verbal intelligence (Ammons & Ammons, 1962). Participants who reported having used a drug of abuse (including alcohol but excluding nicotine and caffeine) at least 20 times in the lifetime were assessed for Diagnostic and Statistical Manual of Mental Disorders (4th edition, DSM-IV) criteria for drug abuse and drug dependence using a checklist (Hudziak et al., 1993) updated for DSM-IV. Inclusion criteria for the cocaine-dependent group included reporting having used cocaine at least weekly during the past 6 months, and meeting a DSM-IV cocaine dependence diagnosis. Inclusion criteria for the control group included a negative urine test for cocaine, and reporting having never used cocaine. Exclusion criteria for all subjects included any lifetime history of in-patient psychiatric treatment, treatment with psychiatric medications within the past six months, or meeting current or retrospectively applied dependence criteria for any drug other than cocaine for the cocaine-dependent-group (including alcohol; excluding nicotine and caffeine). The two groups were matched on the variables of gender, marital status, age, years of education, intelligence score, monthly income from all sources, and tobacco cigarettes smoked per day. Therefore, as the study progressed, some participants who were screened for the study and met eligibility criteria were nonetheless excluded because inclusion would have caused the groups to differ on one or more matching variables. Those participants who were not excluded stayed for the remainder of the session. Those who did not meet inclusion criteria were provided for \$30 for participating in the laboratory screening.

Demographics for the 20 cocaine-dependent and 20 control participants are presented in Table 1. The groups did not differ significantly on any matching variable. There was a trend for older age in the cocaine group. However, previous data on delay discounting and age indicate this age difference would bias against the hypothesis of greater discounting in the cocaine group (Green, Fry, & Myerson, 1994; Green, Myerson, Lichtman, Rosen, & Fry, 1996; Green, Myerson, & Ostaszewski, 1999). The number of participants meeting criteria for alcohol and marijuana abuse also did not significantly differ between groups. As expected, several variables related to cocaine use were significantly higher in the cocaine group. Urine tests showed cocaine-positive results for 17 of the 20 cocaine dependent volunteers.

Apparatus

Experimental sessions were conducted in an isolated corner of a room for conducting multiple experimental sessions. Participants for this study were seated individually at a desk upon which a computer, monitor, keyboard, computer mouse, and coin dispenser (Telequip Transact 2+ CE, Crane Payment Solutions, Salem, NH) were located. A research assistant conducted the experimental sessions and remained in the room, positioned behind the

participant as he or she was facing the computer monitor, while the participant completed all tasks.

Procedure

After screening, participants completed a variety of tasks in a randomized order, including the tasks described below. Other tasks were performed that are not relevant to the present analyses and are therefore not discussed.

QDOT—This computerized task (programmed in ZBasic) used a coin dispenser for money reward delivery, a feature based on the innovative use of coin dispensers with the EDT (Reynolds & Schiffbauer, 2004). A visual depiction of the task is shown in Figure 1. Before beginning the task participants were instructed to sit at the desk with eyes open during any waiting periods in the task, and were forbidden from engaging in other behaviors such as reading. The task consisted of 20 discrete choices between a smaller immediate reward presented in a box on the left side of the screen (e.g., “get 40 cents now”) and an 80¢ delay reward presented in a box on the right side of the screen (e.g., “wait 5 seconds to get 80 cents”). A response button that could register a mouse click was underneath each of the two boxes. At the top center of the screen was a box displaying total earnings on the task. On any trial, if the smaller sooner reward was selected with a single mouse click, the response options disappeared and a button appeared that stated “Click here to bank your [amount] cents.” Upon a single mouse click on this button, that amount was dispensed from the coin dispenser, and the total earning box was updated. If the delayed 80¢ was selected, the response options disappeared and a number in the middle of screen counted down the number of seconds to wait (i.e., counter decreased by 1 every second). When the delay elapsed, a button appeared that required the participant to click to “bank” the 80 cents, at which point the coins (e.g., quarters, dimes, nickels) were delivered and the total earnings were updated. When money was delivered, participants removed the coins from the dispensing tray and dropped them into a glass jar.

There were 5 blocks of 4 trials each, with each block associated with a different delay for the 80 cent reward. The delays were 5, 10, 20, 40, and 80 seconds, and followed an increasing order across blocks. On the first trial of each block, the immediate reward size was 40¢ (i.e., 50% of 80¢). The smaller reward was then adjusted within the block using a “decreasing adjustment” algorithm, which has been used in previous human studies involving hypothetical rewards (Du, Green, & Myerson, 2002; Kowal, Yi, Erisman, & Bickel, 2007). Specifically, the smaller sooner reward was adjusted by 20, 10, and 5¢ on trials 2, 3, and 4 of the block, respectively, in the direction that would move choice toward indifference (e.g., the smaller reward on the second trial of the block would be either 20¢ if the immediate 40¢ had been selected on the first trial, or 60¢ if the delayed 80¢ had been selected). The indifference point was defined as the value that would have been presented on a 5th trial (although there was not a 5th trial) had the algorithm continued (i.e., an adjustment of 2.5¢). Indifference points therefore varied by increments of 2.5¢, and were divided by 80¢ to be expressed as the proportion of the larger reinforcer.

A waiting period was imposed after the final trial to prevent participants from choosing the smaller immediate reward to end the task or session sooner (which potentially confounds monetary reinforcement with the reinforcing or punishing qualities of the experimental context). Participants were told before beginning the task that the total duration of the task would be independent of the choices made during the task, although participants were not explicitly told about the waiting period at the end of the task that was responsible for ensuring approximately equal task duration. The waiting period was defined as 660 seconds minus the sum of all larger reward delays that the participant experienced throughout the

task. Although this manipulation ensured that total programmed waiting time did not differ across participants, differences in participant response latency nonetheless allowed for some variability in total task time. At the end of the task, participants exchanged whole dollar amounts of coins for paper currency.

EDT (Reynolds & Schiffbauer, 2004)—This task has been used in a variety of studies (Krishnan-Sarin et al., 2007; Reynolds & Schiffbauer, 2004; Reynolds et al., 2006; Reynolds, 2006a; Shiels et al., 2009; Voon et al., 2010). The EDT is a delay-discounting task that provides operant consequences either immediately or after a delay in response to choices. Consequences were delivered via an automatic coin dispenser, which was the same model as used for the QDOT. On each trial, the participant made choices between a 30¢ delayed reward (delays of 0, 7, 14, and 28 s across blocks) at a 35% probability of receiving the reward, and an amount of immediate and certain money that adjusted in magnitude across trials. The delays used in the present study correspond to the most recent version of the EDT (Voon et al., 2010), while previous studies using the EDT utilized delays with a maximum value of 60 s. The Immediate money magnitude adjusted according to an algorithm (Reynolds & Schiffbauer, 2004). At the end of the task, participants exchanged whole dollar amounts of coins for paper currency.

Hypothetical \$1,000 Delay-Discounting Task (Johnson & Bickel, 2002)

This task has been used in a variety of studies (Baker, Johnson and Bickel, 2003; Heil, Johnson et al., 2006; Johnson and Bickel, 2002; Johnson et al., 2007; Yi, Johnson, & Bickel, 2005; Yoon et al., 2007; Johnson et al., 2010). Participants made a series of choices between receiving a \$1,000 delayed hypothetical reward and an adjusting smaller immediate reward. The magnitude of the smaller immediate option was adjusted across trials according to a previously described algorithm (Richards, Zhang, Mitchell, & de Wit, 1999) until an indifference point was determined. Each new choice was displayed on the screen for 1 s before the participant could use the mouse to register a response by clicking on one of the two options. Once an indifference point was determined, the larger later option was delayed further and the adjustment procedure was repeated with that new delay. The present value of the larger later option was assessed at seven different delays: 1 day, 1 week, 1 month, 6 months, 1 year, 5 years, and 25 years.

Potentially Real \$10 Delay-Discounting Task (Johnson & Bickel, 2002)—

Discounting for a potentially real \$10 reward was conducted with a previously used task (Baker, Johnson and Bickel, 2003; Johnson and Bickel, 2002; Johnson et al., 2007). This procedure is identical to the \$1,000 hypothetical task with a few exceptions: 1) the larger later reward was \$10 rather than \$1,000; 2) the task included only four delays rather than seven (1 day, 1 week, 1 month, 6 months); 3) the consequence from one randomly selected trial from all the choice trials in this condition was provided to the participant. That is, either the smaller immediate amount was added to the study earnings delivered at the end of the session, or the larger later reward was provided to the participant after the stated delay on that trial, depending on which of the two options the participant selected on that trial. If the delayed reward had been selected, the participant was given the option to either pick up the money at the laboratory after the specified delay, or to have the money mailed to him or her after the delay. The reward contingency was fully explained to the participant before performing the task, and the participant was instructed to make every decision as if it were a real choice because there was an equal chance that each trial involved the consequence that will actually be received.

Data analysis

Demographics between the two groups were compared with independent samples t-tests, with the exceptions of gender and marital status, which were compared with Fisher's exact tests. Equal variance was assumed for t-tests with the exceptions of money spent on cocaine per week, days cocaine used per week, and duration of cocaine use. A previously published algorithm (Johnson & Bickel, 2008) was used to objectively assess the orderliness of discounting data from the QDOT. Components of the Johnson and Bickel (2008) algorithm have been utilized in a wide variety of delay-discounting studies to provide an objective metric of the orderliness of discounting data (Beck & Triplett, 2009; Bobova, Finn, Rickert, & Lucas, 2009; Herting, Schwartz, Mitchell, & Nagel, 2010; Johnson et al., 2010; Lawyer, Williams, Prihodova, Rollins, & Lester, 2010; Melanko, Leraas, Collins, Fields, & Reynolds, 2009; Mitchell & Wilson, 2010; Rasmussen, Lawyer, & Reilly, 2010; Saville, Gisbert, Kopp, & Telesco, 2010; Sellitto, Ciaramelli, & di Pellegrino, 2010; Wilson, Mitchell, Musser, Schmitt, & Nigg, 2011). Specifically, the algorithm identified discounting functions in which any delay's rating was at least 0.2 greater than the delay preceding it, starting with the second delay.

For each discounting task for each participant, the indifference points were fit to the hyperbolic decay model (Mazur, 1987) using nonlinear regression: Indifference point (as proportion of larger reward) = $1 / (1 + k \times \text{Delay})$. The resulting value of the free parameter k served as an index of the rate of discounting, with higher values corresponding to greater relative preference for smaller sooner rewards. Because the time unit of days was used in nonlinear regression, all k values carried the units of days^{-1} . Because k values were positively skewed, a $\log_{10}$ transformation was applied to normalize k values. Pearson correlations were conducted among transformed k values for the four discounting tasks in the pooled sample across both groups, and within each of the two groups. Cohen's d , using the pooled standard deviation between groups, was calculated for each delay-discounting task to assess the effect size of the difference in transformed k values between the cocaine and control groups. For each of the four tasks, the value of the discounting parameter k resulting from nonlinear regression was compared between the cocaine and control groups with an extra sum-of-squares F test analyzing all individual participant indifference point data using GraphPad Prism® v. 5. As described elsewhere (Motulsky & Christopoulos, 2003), this method calculated the error variance for indifference points when: 1) assuming two best fitting k values (one k value fit for each of the two groups), and 2) assuming a single k value fit to all of the data across both groups. Significant differences in error variance between these methods indicate that the k values significantly differ between the two groups. To examine potential sex differences, F tests were also used to compare males to females on each of the discounting tasks while combining the cocaine and control groups. All statistical tests were two-tailed and α was considered .05.

Results

Orderliness of QDOT data

Figures 2 and 3 show individual participant delay-discounting functions for the QDOT in the control and cocaine-dependent groups, respectively, with hyperbolic decay functions fit to the indifference points. Eight control participants (Control 3, 38, 39, 45, 46, 47, 49, and 63) showed a nearly flat function with maximal reinforcing value (approximate indifference point proportion of 1.0) remaining even at the longest delay of 80 s, while only four cocaine-dependent participants (Cocaine 19, 59, 61, and 62) showed this pattern. All remaining 28 participants showed generally monotonically decreasing functions with delay. The Johnson & Bickel (2008) algorithm detected only one control group participant (Control 32) and three cocaine group participants (Cocaine 9, 16, and 26) whose data showed that any delay's

rating was at least 0.2 greater than the preceding delay. Of these four participants, only a single indifference point deviated from orderliness by this criterion, and the fitted hyperbolic decay function appeared to reasonably model the reduction in indifference point with delay.

Comparison of discounting task logistics across tasks

Table 2 shows the number incomplete discounting functions, task duration, and money earned for each of the two groups across the four delay-discounting tasks. The QDOT, hypothetical \$1,000 task, and potentially real \$10 task never failed to converge upon an indifference point for any delay for any participant. The EDT failed to provide a complete data set for one participant in the cocaine-dependent group. Also shown in Table 2, at a mean duration of approximately 16 min, the QDOT was approximately 2.5 fold faster than the EDT, which had a mean duration of approximately 39 min. The QDOT duration was greater than the hypothetical \$1,000 and potentially real \$10 task durations, which were both approximately 5–6 min. Not only was the mean duration of the QDOT substantially shorter than the EDT, the variability in duration was substantially smaller in the QDOT compared to the EDT. Tasks earnings are also shown in Table 2. The QDOT provided mean earnings that were intermediate between the EDT, which generated the greatest earnings, and the potentially real \$10 task, which generated the least earnings. Additionally, the range of values earned during the QDOT was substantially smaller than for the other two discounting tasks in which actual money was earned.

Comparison of group differences across tasks

Figure 4 shows the group median indifference points for the cocaine and control participants for each of the four delay-discounting tasks, with hyperbolic decay functions fit to the median data. For each task with the exception of the potentially real \$10 task, the cocaine group showed greater discounting than the control group. For the potentially real \$10 task, both groups discounted to a similar degree. Table 3 shows the mean $\log_{10}(k)$ for both groups, as well as effect size as indexed by Cohen's d . Note that the hyperbolic decay functions in Figure 4 correspond to the single k values fitting the median indifference point data, which are distinct from the means of the groups' transformed k values, upon which Cohen's d was based. Consistent with the median data displayed in Figure 4, Cohen's d was relatively large and similar for the QDOT, the EDT, and the hypothetical \$1,000 task, ranging from 0.40 to 0.50, approximately corresponding to a “moderate” effect by conventional standards (Cohen, 1988). Cohen's d was substantially smaller for the potentially real \$10 task at 0.14. Consistent with the median data shown in Figure 4 as well as the analysis of effect size, Table 3 also shows that the F tests determined that k was significantly different between the two groups for the QDOT, the EDT, and the hypothetical \$1,000 task, but was not significantly different between the groups for the potentially real \$10 task.

Comparison of males ($n=23$, except $n=22$ for the EDT) versus females ($n=17$) collapsed across the cocaine and control groups revealed no significant sex differences in discounting for the QDOT ($F(1,198)=0.001$, $p=.98$), the EDT ($F(1,154)=0.195$, $p=.20$), the \$1,000 hypothetical task ($F(1,278)=0.268$, $p=.60$), and the \$10 real task ($F(1,158)=0.047$, $p=.83$).

Correlations among the delay-discounting tasks

Table 4 shows Pearson's correlations among the $\log_{10}(k)$ pooled across both groups for each task. The directions of all correlations were positive. The only statistically significant correlation was that between the QDOT and the EDT. The correlation between the hypothetical \$1,000 and potentially real \$10 tasks approached significance. Pearson's correlations within each of the two groups were generally consistent with these results. Specifically, within the cocaine dependent group the only significant correlation was a

positive correlation between the QDOT and EDT ($n=19$, $r=.541$, $p=.02$). Within the control group no correlations were significant but the positive correlations between the QDOT and EDT showed a trend toward significance ($n=20$, $r=.385$, $p=.09$).

Discussion

The novel QDOT showed systematic effects of delayed monetary reinforcement in the human laboratory over the course of 80 s, using 100% choice delivery, and with a task duration of less than 20 min. The effect of delay followed a hyperbolic decay model widely found to describe human and nonhuman animal delay discounting (e.g., Mazur, 1987; Rachlin et al., 1991). Human operant reinforcement studies have traditionally had difficulty in showing sensitivity to delay (e.g., Hyten, Madden, & Field, 1994; A. W. Logue, King, Chavarro, & Volpe, 1990; A. W. Logue, Pena-Correal, Rodriguez, & Kabela, 1986). Moreover, human delay discounting research using hypothetical and potentially-real choice procedures have typically shown decreases in reward value with relatively long delays measured by days, months, and years. In contrast, delays on the order of seconds have been shown to cause non-trivial decreases in reinforcement in humans when utilizing immediately-usable, non-monetary reinforcers, including video clips (Navarick, 1996; Navarick, 1998) and consumable liquids (Jimura, Myerson, Hilgard, Braver, & Green, 2009; McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007). One hypothesis is that the tendency towards self-control (i.e., larger later reinforcer) responding traditionally observed in human operant research is due to the use of token reinforcers that cannot be exchanged for other goods until after the session (Jackson & Hackenberg, 1996). The EDT and QDOT may be able to show human delay discounting for monetary rewards over such short time frames because reinforcement entails actual coin delivery, not just token reinforcement (e.g., an earnings total on a screen which is exchanged for real money after the task). While money itself is a token reinforcer and cannot be exchanged for other goods until leaving the laboratory, it is possible that money is so extensively generalized that its physical acquisition is delay discounted more similar to immediately-useable reinforcers than to other token reinforcers typically used in human operant research (e.g., points or earnings displayed on a screen). A comparison of QDOT performance with and without coin delivery throughout the task would provide a test of this unexamined hypothesis.

Performance on the QDOT was significantly, positively correlated with performance on the EDT. Similarly, a trend was evident for discounting in the hypothetical \$1,000 task to be positively correlated to discounting in the potentially real \$10 task. Although previous research has shown EDT performance to be positively correlated with hypothetical delay-discounting performance (Reynolds, 2006a), the present study did not find this effect. QDOT and EDT performance may be similar because both tasks provide operant reinforcement during the task, involve relatively small magnitude reinforcers, and assess short time frames. In contrast, the hypothetical \$1,000 and potentially real \$10 tasks do not provide operant reinforcement during the task, involve larger rewards, and relate to timeframes involving one day to at least six months. Consistent with the distinction between the two types of tasks, the EDT but not a potentially real reward task was affected by ethanol administration (Reynolds et al., 2006). Moreover, the EDT but not a hypothetical rewards task was affected by methylphenidate administration (Shiels et al., 2009). Therefore, procedures such as the QDOT and EDT may be closer to “state” measures, while hypothetical and potentially real tasks may be closer to “trait” measures (these descriptors likely fall along a continuum), with shorter timeframe contingencies more malleable to experimental conditions. Cocaine-dependent individuals may tend to be less sensitive to delayed reinforcement over both short and long timeframes compared to controls, suggesting that they all can serve as “trait” measures, consistent with the group differences observed for the QDOT, EDT, and hypothetical tasks. The lack of correlation between short

and long timeframe tasks could result from differential sensitivities to different time frames, or from methodological differences.

The QDOT resulted in an effect size between the control and cocaine-dependent groups (Cohen's $d = 0.42$) that compared favorably with the other tasks. That is, this effect was similar to that obtained with the EDT (0.50) and hypothetical \$1,000 task (0.40), and substantially larger than that obtained with the potentially real \$10 task (0.14). Moreover, the effect size obtained with the QDOT was similar to the effect size obtained with the hypothetical \$1,000 task between cocaine-dependent and matched control participants in a previous study (0.53) (Heil et al., 2006). These data suggest that the QDOT is sensitive to the types of between group differences that have been examined so frequently in the delay-discounting and drug-dependence literature. Although the effect size obtained with the EDT was somewhat larger than the QDOT, the EDT involves probabilistic as well as delayed reinforcement. Therefore differences in probability discounting may have contributed to this increased effect size. The small effect size (0.14) between the control and cocaine groups for the potentially real \$10 task was surprising. Previous research has shown this task to correlate well with a hypothetical task (using the same reward magnitude for both tasks, which was not the case in the present study) (Johnson & Bickel, 2002). Moreover, the \$10 potentially real reward task showed greater discounting in heavy smokers than demographically matched nonsmokers, with Cohen's $d = 0.84$ (Baker et al., 2003). The task also showed light smokers to discount more than demographically matched nonsmokers, with Cohen's $d = 0.57$ (Johnson et al., 2007). It is not clear why the potentially real reward task showed large effects in these studies comparing tobacco smokers to controls, but showed a relatively small effect (and no significant difference) in the present study comparing cocaine-dependent and control participants.

Despite the relatively large difference in delay discount effect size between groups on the QDOT, mean total earnings on the QDOT for the control group was \$0.89 (~7%) greater than for the cocaine group, a relatively small difference. However, because task duration was not choice-dependent (told to participants before beginning) and session duration was extremely similar between groups, it cannot be argued that the cocaine group was behaving more efficiently.

Consistent with the effect size analysis, the QDOT, EDT, and hypothetical \$1,000 tasks showed that the cocaine-dependent participants discounted significantly greater than the control participants, replicating previous findings regarding cocaine abusing/dependent individuals using hypothetical delay discounting tasks (Coffey et al., 2003; Heil et al., 2006) and a potentially real reward delay discounting task (Kirby & Petry, 2004). The lack of significant differences in discounting between the groups on the potentially real \$10 task contrasts with previous results in cocaine abusers using a potentially real reward task (Kirby & Petry, 2004), although it should be noted that the potentially real reward task used in that study differed from the one used in the present study.

The QDOT may provide advantages for particular human delay-discounting studies, although it would not be the best alternative for all experimental questions. First, the QDOT does not confound delay discounting with probability discounting. That is, the QDOT provides certain reinforcers on all trials, and involves no aspect of probabilistic reinforcement. In contrast, in the EDT the larger delayed reward is probabilistic, a characteristic which was suggested by pilot work to increase the reliability of observing a discounting gradient (Reynolds & Schiffbauer, 2004). Although many real-life choices involve options that are both delayed and probabilistic, emerging evidence suggests that delay and probability discounting are similar yet independent processes. For example, reward magnitude is inversely related to discounting rate for delay discounting, but is

directly related to discounting rate for probability discounting (Estle, Green, Myerson, & Holt, 2006). Also, research suggests that delay and probability interact in a complex fashion. For example, when assessing rewards that are both a delayed and probabilistic, the effect of probability is greater at smaller than larger delays, and the effects of reward magnitude on discounting rate in these combined delayed and probabilistic rewards follows the direction normally observed for delay rather than probability discounting (Yi, de la Piedad, & Bickel, 2006).

The second advantage of the QDOT is its substantially shorter and less variable task duration. The mean duration of the QDOT, including instructions, was approximately 16 min, with a range that spanned only 2.5 min and a maximal duration of approximately 17 min. This suggests that the task may be readily utilized in a study within a 20 minute time frame, which compares favorably with other human operant delay-discounting tasks (Lane et al., 2003; Reynolds & Schiffbauer, 2004) such as the EDT, with a maximum duration of 70 min and duration that varied over a 42 min range across participants in the present study. The shorter and more reliable duration of the QDOT allows for its use in studies with multiple other measures, or during a drug administration study or other experimental manipulations in which one is interested in assessing effects on delay discounting at relatively discrete time points.

The third advantage is that the QDOT resulted in less variable money payments to volunteers than some human operant delay-discounting tasks. Although the difference in absolute amount earned between the QDOT and EDT is arbitrary given that the magnitude of earnings for either task could be manipulated, the *variability* in earnings was substantially less in the QDOT than the EDT. That is, the QDOT earnings ranged across an approximately 2-fold range, while the EDT varied over an approximately 5-fold range. The potentially real \$10 task (which is not an operant procedure) varied over an approximately 50-fold range. This decreased variability with the QDOT may be important in two respects. First, researchers can make a more accurate estimate of study costs. Second, there may be experimental advantages in reducing the variability of participant earnings, so that differences in study earnings *per se* are less likely to confound other study hypotheses.

The fourth advantage of the QDOT over previous human operant delay-discounting tasks is that the QDOT always converges on an indifference point. Some previous tasks have allowed for the potential of indeterminate indifference points or multiple indifference points for a single delay (Lagorio & Madden, 2005; Lane et al., 2003; Reynolds & Schiffbauer, 2004; Scheres et al., 2006). To deal with this issue, one procedure has used independent raters to subjectively judge indifference points from the raw data, with differences resolved by discussion (Scheres et al., 2006). As was seen in the present data set for one participant, with the EDT indeterminate indifference points are possible. The possibility that the EDT task may not work for an *a priori* unknown number of participants may pose challenges for power analyses and the determination of target sample size for a study. The participant (Cocaine 19) for whom the EDT failed to produce data provides an example worth exploration. That participant emitted 100% of choices for the immediate option on all delay blocks, and therefore the titration algorithm did not converge on a solution. To address the fact that the delayed option is probabilistic and the immediate value is certain in the EDT, all non-zero delay indifference points are divided by the zero-delay block indifference point. Therefore, in the case of Cocaine 19, even if a value of 0 were assigned as the indifference point for each delay, normalization would result in undefined data.

Limitations of the QDOT should be considered. Although the QDOT is more similar to the typical methodology in nonhuman delay-discounting studies because rewards are contingent and experienced throughout the task, there are nonetheless remaining differences. One is

that nonhuman animal studies provide extensive experience with choices until stability in choice is achieved. The QDOT provides only a single exposure to each choice within the procedure. Through both instructions and experience throughout the task, participants presumably learn that consequences will indeed be provided for every option he or she makes. It is possible that the response on the first trial or few first few trials may have differed had those same choices been presented later in the task, given that there was no or limited experience with delays early in the task. Therefore, the results may be different if the task had been repeatedly performed by the participants (e.g., Lane et al., 2003), a hypothesis that may be empirically addressed in future research. Ultimately, the order in the data, including the hyperbolic nature of the delay-discounting functions, and the differences in degree of discounting between control and cocaine-dependent participants, suggests that the task provides a valid assessment of delay discounting. Another limitation is that it is unknown to what extent individual trial duration could have impacted results. Although the instructions and the waiting period at the end of the task provided assurance that early termination of the task did not encourage choice for the smaller immediate reinforcer, inter-trial-interval (individual trial duration or the time between reinforcement deliveries) was decreased by selection of the smaller immediate reward. It is therefore unknown whether results would have differed if inter-trial-interval were held constant (i.e., if an adjustable waiting period were imposed after reinforcer delivery). Previous human contingent delay discounting research has shown that although results can differ depending on whether inter-trial-interval is constant or variable, both methods result in concordance regarding whether or not groups differ in delay discounting (Marco et al., 2009; Scheres et al., 2006). Future research may examine the effect of holding inter-trial-interval constant on the QDOT. Another limitation is that the reliability of the task is unknown. Assessing the test-retest reliability of the task will be important before incorporating the QDOT as a repeated measure in future studies.

Although the present results suggest that the QDOT may be appropriate in some experimental situations, other procedures will be appropriate for other experimental situations. Each of the operant human tasks mentioned in the present studies have made important scientific contributions, and were appropriate for addressing experimental questions in the referenced studies. Advantages of these other procedures have included exposure to forced choice trials (Lagorio & Madden, 2005; Lane et al., 2003; Reynolds & Schiffbauer, 2004); innovative graphical representation that may facilitate participation in children (Scheres et al., 2006), assessing real consequences with delay durations of multiple days (Lagorio & Madden, 2005), and the use of coin delivery which was replicated in the present methods for the QDOT (Reynolds & Schiffbauer, 2004). Because delayed consequences in life are typically uncertain in addition to delayed, the EDT may provide a more face valid model of these conditions (Reynolds & Schiffbauer, 2004). Ultimately, research questions and experimental constraints should determine the nature of the delay-discounting task to be used for a particular study.

In summary, the QDOT showed systematic effects of delay that conformed well to a hyperbolic function, correlated well with the EDT, showed an effect size between cocaine-dependent and control participants that was similar to most other delay-discounting tasks, and found that the cocaine-dependent participants discounted significantly more than the control participants. The QDOT may provide methodological advantages for particular human delay-discounting research because it is not confounded by probabilistic reinforcement, it can be reliably administered in less than 20 minutes, results in a relatively reliable magnitude of session earnings, and consistently results in complete delay-discounting data.

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Figure 1.

Visual depictions of the QDOT. The upper left panel shows a choice screen with the mouse cursor positioned over the larger later reward. The upper right panel shows a waiting-period screen that would be shown if the participant had selected the larger delayed reward. The number in the middle of the screen is the number of seconds remaining during the wait, which was updated every second. The lower left panel shows the screen prompting the participant to “bank” the money reward, which caused coins to drop into the coin dispenser tray. The lower right panel shows the task workspace in which a mock-participant is dropping earned coins into the glass jar after retrieving the coins from the coin dispenser tray (to the left of the glass jar).

Figure 2.
Individual delay-discounting functions for the control group participants with fitted hyperbolic decay functions.

Figure 3.
Individual delay-discounting functions for the cocaine-dependent participants with fitted hyperbolic decay functions.

Figure 4.

Group median indifference points for the cocaine and control participants for each of the four delay-discounting tasks, with hyperbolic decay functions fit to the median data. For the potentially real \$ 10 task both curves are present but are overlapping. Note that for the QDOT and EDT panels the time units on the x-axis are seconds, and for the Hypothetical \$1,000 and Potentially Real \$10 panels the units are days.

Table 1

Participant demographics. Values represent means (SD) with the exception of gender, marital status, alcohol abuse, marijuana abuse, and typical route of cocaine administration.

	Control (n=20)	Cocaine (n=20)	Statistical comparison *
Gender (female count)	9 (45%)	8 (40%)	p=1.0
Marital status (married count)	0 (0%)	1 (5%)	p=1.0
Age (years)	38.3 (11.3)	44.1 (7.6)	t=1.90, df=38, p=.06
Education (years)	12.7 (1.8)	12.6 (1.5)	t=0.24, df=38, p=0.81
Intelligence (Quick Test score)	40.9 (3.7)	39.3 (3.0)	t=1.54, df=38, p=0.13
Monthly income (\$)	875 (737)	909 (631)	t=0.16, df=38, p=0.88
Cigarettes/day	8.0 (12.5)	8.9 (7.7)	t=0.27, df=38, p=0.79
Alcohol abuse (count meeting criteria)	1 (5%)	2 (10%)	p=1.0
Marijuana abuse (count meeting criteria)	0 (0%)	2 (10%)	p=.49
Money spent on cocaine per week (\$)	0 (0)	196.40 (189.60)	t=20.36, df=19, p<.0001 **
Days cocaine used per week	0 (0)	5.0 (2.0)	t=86.88, df=19, p<.0001 **
Duration of cocaine use (years)	0 (0)	21.4 (7.1)	t=29.31, df=19, p<.001 **
Typical route of cocaine administration (count)	n/a	Smoked=18 (90%) Intranasal=2 (10%)	n/a

* Independent samples t-tests except Fisher's exact test for gender, marital status, alcohol abuse, and marijuana abuse. Equal variance was assumed for t-tests with the exceptions of money spent on cocaine per week, days cocaine used per week, and duration of cocaine use.

** Significant

Table 2

Comparison of incomplete discounting functions, task duration, and money earned for each of the two groups across the four delay-discounting tasks. Discounting functions were flagged as incomplete if the task failed to result in one or more indifference points for a participant.

	# incomplete discounting functions		Mean task duration (min) (range)		Mean money earned (\$) (range)	
	Control	Cocaine	Control	Cocaine	Control	Cocaine
QDOT	0	0	15.6 (14.7–16.5)	15.8 (14.6–17.1)	14.57 (8.15–16.00)	13.68 (9.40–16.00)
EDT	0	1	41.7 (29.0–70.0)	36.3 (28.0–53.0)	18.12 (10.60–50.88)	18.45 (10.90–33.57)
Hypothetical \$1,000	0	0	5.8 (4.0–10.3)	4.75 (2.3–7.7)	N/A	N/A
Potentially real \$10	0	0	6.2 (3.0–10.0)	5.4 (2.0–10.0)	7.00 (0.60–10.00)	8.38 (0.20–10.00)

Table 3

Comparison between cocaine-dependent and control participants on the four delay-discounting measures. Because the time unit of days was used in nonlinear regression, all k values carry the units of days⁻¹. Cohen's d was calculated with the pool standard deviation between groups. For each group and all conditions $n=20$, except for the EDT in the cocaine group, for which $n=19$.

	Mean $\log_{10}(k)$ (SD) *		Cohen's d	F test
	Control	Cocaine		
QDOT	2.68 (0.81)	3.00 (0.75)	0.42	$F(1,198)=7.99, p=.005^*$
EDT	1.97 (1.96)	2.93 (1.91)	0.50	$F(1,154)=27.59, p<.0001^*$
Hypothetical \$1,000	-2.37 (1.07)	-1.89 (1.31)	0.40	$F(1,278)=7.19, p=.008^*$
Potentially real \$10	-1.42 (1.28)	-1.27 (0.96)	0.14	$F(1,158)=0.54, p=.46$

* Significant

Table 4

Pearson's correlations of $\log_{10}(k)$ among the four tasks. For correlations involving the EDT $n=39$, and in all other correlations $n=40$.

	QDOT	EDT	Hypothetical \$1,000	Potentially real \$10
QDOT	--	$r=.49$ $p=.002^*$	$r=-.06$ $p=.72$	$r=.07$ $p=.66$
EDT		--	$r=.15$ $p=.37$	$r=.16$ $p=.33$
Hypothetical \$1,000			--	$r=.27$ $p=.10$
Potentially real \$10				--

* Significant