A Delay Discounting Primer

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"Impulsivity" is a colloquial term with which nearly everyone has some commerce. Although the term is sometimes used to describe socially appropriate actions (e.g., "she possessed an impulsive force to succeed in her job"), more often it refers to problematic behavior. For example, children are described as "impulsive" when they take a toy from a peer without considering the likely consequences of doing so (e.g., the peer crying and a reprimand from a caretaker). College students are said to be "impulsive" when they choose to attend a party with friends rather than study for an exam scheduled for the next day. And a middle-aged adult might be similarly described if he/she repeatedly buys things "on impulse" without considering that payments (with interest) will come due at the end of the month. In this more frequent usage impulsivity describes a tendency to act on a whim and in so doing to disregard a more rational long-term strategy for success.

Psychologists have long measured impulsivity as an aspect of personality using self-report measures such as the Barratt Impulsivity Scale (BIS-11, Patton, Stanford, & Barratt, 1995) or the Eysenck Personality Questionnaire (EPQ, Eysenck & Eysenck, 1978). Such measures quantify impulsivity as it occurs in natural human environments by asking individuals to report on their tendencies to "act on impulse", "spend more than I earn", or "plan tasks carefully". Psychologists and psychiatrists have also classified a number of disorders as related to failures of impulse control. These include attention deficit hyperactivity disorder, substance abuse, kleptomania, pathological gambling, eating disorders, and trichotillomania, among others (e.g.,

American Psychiatric Association, 2000; Barkley, 1997). Each of these disorders is characterized either by a failure of attention, a failure to inhibit a response, and/or a failure to consider the probable negative long-term outcomes of the behavior.

In accordance with the activities of personality and clinical psychologists, the last several decades have seen experimental psychologists studying similar categories of impulsive behavior. For example, failure of attention (e.g., Robbins, 2002), inability to inhibit pre-potent responses (e.g., Winstanely et al., 2005), and the devaluation of future events (e.g., Ainslie, 1975) have received much attention. With recent findings that the latter two appear to precede and predict drug taking in rodents (Dalley et al., 2007; Diergaarde et al., 2008; Carroll, Anker, Mach, Newman, & Perry, this volume), we anticipate these activities will be the focus of much study of impulsivity and addictive behaviors for years to come. Because the primary focus of the remainder of this book is choice and the failure of future events to affect current decisions, this primer is limited to two types of this form of impulsive choice: (a) preferring a smaller-sooner reward while forgoing a larger-later one and (b) preferring a larger-later aversive outcome over a smaller-sooner negative event. Considering the first of these, when an impulsive choice occurs we may infer that the subjective value of the smaller-sooner reward is greater than the value of the larger-later one. Said another way, the choice suggests that the value of the larger-later reward has been discounted; a process referred to as *delay discounting*, the primary subject of this text. Delay discounting describes the process of devaluing behavioral outcomes, be they rewarding or aversive events, which happen in the future (and perhaps the past, see Yi, Mitchell & Bickel, this volume).

Delay discounting would seem to be of relevance to what personality psychologists measure as “impulsivity” but this has not proven to be the case (e.g., Crean, de Wit, & Richards,

2000; Monterosso, Erhman, Napier, O'Brien & Childress, 2001). Delay discounting, however, correlates with a host of impulse-control and psychiatric disorders including substance abuse (Yi et al., this volume), pathological gambling (Petry & Madden, this volume), ADHD (Barkley, 1997; Williams, this volume), and borderline personality disorder (Crean et al.), to name just a few. These findings have generated considerable interest in delay discounting as a trait predictive of these disorders (e.g., Carroll et al., this volume) or as a state affected by experimental manipulations (e.g., Odum & Baumann, this volume).

This chapter provides a primer in delay discounting; it is intended for readers who have only a limited background in the procedures, measures, and outcomes of studies examining this form of impulsive choice. Following an overview of the delay discounting process, its quantification, and implications for the human condition, emphasis is placed on procedures (and critiques of these procedures). The remainder of the book is concerned with experimental findings and, for the most part, we will not review these here.

Delay Discounting

As noted above, one investigative approach to impulsivity has been to study preference between smaller-sooner and larger-later consequences. When these consequences are positive reinforcers such as food for a hungry pigeon, choosing the smaller-sooner reward is regarded as impulsive because of the long-term detrimental outcome of the choice (less food). This paradigm has also been used to study choices between smaller-sooner and larger-later aversive events (Hineline, 1977; Mischel, Grusec & Masters, 1969). As before, the impulsive choice results in an immediate benefit (e.g., a shock-free period) but a delayed detrimental outcome (a more intense shock). This general paradigm has also been extensively used in studying impulsive decisions in humans choosing between smaller-sooner and larger-later gains and losses. Together the

nonhuman and human literatures have yielded a systematic set of findings that have proven amenable to quantification and replication. These findings and their apparent relevance to socially important patterns of behavior have generated substantial interest in studying impulsivity and its causes.

Exponential Discounting

Assuming that natural selection favors organisms which choose the better of two behavioral outcomes, delay discounting appears enigmatic because preferring a smaller-sooner over a larger-later reward fails to maximize income. Likewise, preferring a larger-later over a smaller-sooner aversive event (like an electric shock) is seemingly irrational because it fails to minimize an event which may endanger the organism. What would be the advantage (from an evolutionary perspective) of discounting the value of temporally delayed events? As eloquently, and more comprehensively, outlined by Stevens and Stephens in their chapter of this volume, an organism which forgoes an inferior but immediate food item, mate, or hiding place in favor of a superior but delayed alternative may find the superior food was consumed by a conspecific during the delay, or that the genetically more fit mate was not receptive to one's advances, or (worst of all) that the better hiding place could not be reached before the pursuing predator captured its "self-controlled" prey. In other words, in the lawless (red in tooth and claw) world of our evolutionary ancestors, a bird in the hand was better than two in the bush if there was a good chance that the bush would be empty upon arrival (if one arrived at all).

In modern human affairs there remain ample reasons for discounting the future. Your brother-in-law may promise to pay you the money he owes (with interest) in a year, but in the interim period he may fall upon hard times and not be able to keep his promise. Although you plan to live to enjoy the benefits of your retirement account, you may be hit by a bus tomorrow

and if you were alive to feel so, would regret the immediate pleasures forgone in favor of investing in the future. Ultimately, the only certain feature of an environment is its uncertainty; or as Heraclitus (535 B.C. - 475 B.C.) put it "Nothing endures but change." In turn, our species and others appear to be as acutely sensitive to differences in reward probability as we are to disparities in delay (Patak & Reynolds, 2007). Indeed, some researchers have suggested that probability and delay have related effects upon the subjective valuation of outcomes (e.g., Rachlin, Logue, Gibbon, & Frankel, 1986); a topic considered in greater depth by Green and Myerson in this volume.

Economists have tackled the discounting of delayed outcomes for some time and have proposed that just as the value of money in a savings account compounds with interest over time, so too should the value of future goods be discounted in a compounding fashion as the delay to their delivery increases (e.g., Samuelson, 1937). Such compounded discounting would be expected if organisms evolved in environments in which the probability of receiving the larger-later outcome decreased in a compounding fashion with each additional unit of delay. One might expect species differences in the rate at which delayed outcomes are discounted if a species evolved in a niche in which delayed outcomes were more or less likely to be received, but the form the discounting function should be the same – an exponential decay function reflecting a compounding decline in value as delays increase:

$$V_d = Ae^{-kd} \qquad (1)$$

In Equation 1, V_d *is* the discounted value of the future reward, A is the reward amount, d is the delay until reward delivery, and k is the discounting rate.

Figure 1 illustrates two exponential discounting curves, each obtained by setting amount (A) to 100 units, delay (d) to the continuum of values along the x-axis, and discounting rate (k) to

the different values shown in the legend. For the upper curve $k = 0.05$; a modest rate of discounting. At a delay of 10 months the delayed reward has lost 40% of its subjective value. If our hypothetical discounter with $k = 0.05$ is asked to choose between 60 units of the good now and 100 units following a 10-month delay, then she is indifferent between the two.[1] As shown by the horizontal dashed line in Figure 1, the discounted value of the delayed reward is equal to that of the immediate one (both equal to 60 units); hence indifference. Given the same choice between these immediate and delayed outcomes, another consumer discounting at a rate of $k = 0.20$ strongly prefers the smaller-sooner outcome - the 60 units available now far exceed the discounted value of 100 units later (now worth only 13 units). Thus, k in Equation 1 may be interpreted as the rate of delay discounting.

Where do Discounting Curves come from?

To obtain a delay discounting curve we need to describe how the value of an event (be it a reward or an aversive event) declines as the delay to its delivery increases. To illustrate, imagine winning a lawsuit and, after paying your lawyer, receiving a guaranteed annuity worth $100,000. One of the terms of the settlement is that the annuity cannot be cashed for 10 months. Not to worry, there are many companies in the "delay discounting business" who will purchase your annuity by giving you less than $100,000 in cash. The fact that these companies pay less than the face value of the annuity illustrates the basic point that delayed rewards are discounted in value but generating a discounting curve will require more specificity.

Imagine that one of these companies offers to give you $70,000 for your annuity and you take it. If you make this choice then it should be clear that the annuity lost more than 30% of its value because of the 10 month delay. If you discounted the delayed annuity by only 20% it would be subjectively worth $80,000 and you would have refused the offer to purchase your

annuity ($70,000 cash < $80,000 subjective value → refuse offer). If you discount the annuity by exactly 30%, then you would have viewed the company's offer ($70,000 in cash) as equal to the subjective value of the annuity ($70,000) and you would have found it difficult to choose between accepting the offer or waiting 10 months to obtain the full $100,000 settlement.

However, you accepted the offer so we know that you are discounting the delayed reward by more than 30%. To determine exactly how much more, we will gradually reduce the settlement offer until you are *indifferent* between accepting it and waiting to receive the entire annuity. The amount of the offer at the indifference point is the discounted value of the delayed annuity – any smaller settlement offer would be rejected and any larger offer would be accepted. For our purposes, we will assume that an indifference point was reached when the offer was $60,000. We can now return to Figure 1 to illustrate how the value of the delayed reward at this indifference point can be used to determine the discounting curve. If we think of the y-axis values as percentages of $100,000, then at a 10 month delay the discounted value of the delayed annuity is worth 60% of its full value. Thus, the indifference point tells us the discounted value of the delayed reward. Because the indifference point is expressed in terms of money available now, the indifference point is often referred to as the *present value* of the delayed reward.

Our economic thought experiment has given us only one present value along the discounting curve. To obtain more values we would repeat the experiment using delays spanning the range shown along the x-axis of Figure 1. With indifference points plotted at seven or eight different delays, we would simply use nonlinear regression techniques (available in most commercially available spreadsheet and graphics software) to fit these data points using Equation 1 – the exponential discounting equation.

Hyperbolic Discounting

Despite its rationality, systematic deviations from the discounting predicted by Equation 1 have been documented in human subjects (e.g., Green, Fry, & Myerson, 1994; Kirby, 1997; Ohmura, Takahashi, Kitamura, & Wehr, 2006; Rachlin, Raineri, & Cross, 1991; Simpson & Vuchinich, 2000) including individuals addicted to drugs (e.g., Bickel, Odum, & Madden, 1999; Madden, Bickel, & Jacobs, 1999; Odum, Madden, & Bickel, 2002), regardless of whether the outcomes were real or hypothetical (e.g., Johnson & Bickel, 2002; Madden, Begotka, Raiff, & Kastern, 2003) or whether delayed gains or losses were considered (e.g., Murphy, Vuchinich, & Simpson, 2001; Odum et al.). Systematic deviations from exponential discounting have also been extensively documented in animal laboratory experiments in which rats and pigeons choose between immediate and delayed food rewards (for a reviews see Logue, 1988; Mazur, 1997) or immediate and delayed aversive events (e.g., Deluty, 1978). Instead, these studies have generally supported the following hyperbolic discounting equation (Ainslie, 1975; Mazur, 1987):

$$V = \frac{A}{1 + kd} \qquad (2)$$

where the parameters are the same as in Equation 1.

Figure 2 illustrates median discounted values of hypothetical delayed monetary rewards from 39 non-smoking, non-drug using human participants in the experiment conducted by Madden, Petry, Badger, and Bickel (1997). These data serve to illustrate the systematic differences which have been extensively documented between empirically obtained discounting (open data points) and the fits provided by Equation 1 (dashed curve; for a review see Green & Myerson, 2004). Within the range of more-brief delays (1 day to 52 weeks), which are expanded in the inset graph, the exponential discounting function overestimates the discounted values of the delayed rewards, while in the upper range of delays the curve tends to underestimate the

discounted values of the rewards. By comparison, the hyperbolic discounting equation more closely fits the obtained data and, as noted above, this outcome is far from unique to this study

It should be noted that other discounting functions have been suggested. For example, Green and Myerson (2004) demonstrated that significantly better fits of human discounting data are provided by adding an exponent to the denominator of Equation 2 (Green & Myerson referred to this as a hyperbola-like equation). As noted by these authors, better fits are not surprising when one adds a free parameter to any equation but they argue that the addition is required when it is important to precisely describe the shape of the delay discounting function, or to precisely quantify the rate of delay discounting in individual or groups of humans subjects. The latter raises a problem with the hyperbola-like equation (one noted by Green & Myerson): When the value of the exponent is not equal to 1.0 the discounting parameter (k) cannot be interpreted as a simple quantitative measure of delay discounting. A second problem with the hyperbola-like equation is that several experiments involving rats and pigeons have found that adding the exponent does not appear to improve the fits provided by Equation 2 (e.g., Green, Myerson, Shah, Estle, & Holt, 2007; Rodriguez & Logue, 1988; Mazur, 1986, 1987, 2007). Whether this human/animal difference is due to obvious differences in species or to procedural differences (e.g., humans have far less, or no, exposure to the outcomes of their choices and almost never experience the delays to the rewards before making their choices) is currently unknown.

Given the debate surrounding the different discounting equations we offer the following advice. If the researcher is primarily concerned with determining the shape of the delay discounting function then this is an empirical question and one should fit more than one equation. By comparing the relative fits provided by different equations one can obtain the best

description of your data.[2] However, if the goal is to quantifying the sensitivity to delay, then all of these equations should be avoided. Instead, the researcher should calculate the area under the obtained indifference points. The area under the curve solution was suggested by Myerson, Green, and Warusawitharana (2001) and it offers a hypothesis-free measure of degree of delay discounting. Because area under the curve is calculated using every indifference point, the measure of sensitivity to delay is affected by obtained data rather than estimated from a free parameter of an equation which, in some cases, may not provide a good fit of the data. An additional benefit is that frequency distributions of area under the curve values taken from a sample of subjects are usually normally distributed, making this measure amenable to parametric inferential statistical analyses. Readers interested in the quantitative details of calculating area under the curve should consult the Myerson et al. paper.

Preference Reversals

A second problem with exponential discounting is that it predicts rational choices which are simply not observed either in our everyday lives or in the laboratory. By "rational" we mean that, all else being equal, preference should remain constant over time. However, such preference consistencies would mean that when I chose to join a health club I would not subsequently change my mind and stop working out (even though I continue to pay for the privilege of doing so). Similarly, millions of people each year commit to a diet by purchasing several months of low-calorie mail-order meals, but later decide that a hamburger today is more worthwhile than the slow weight losses that would be obtained if only the diet could be followed. Such *preference reversals* are common. We know we should put more money into our retirement account but fail to do so. We know that our long-term family relationships benefit from daily nurturing but we

continue to watch television. We promised marital fidelity but our divorce rates suggest we too often change our minds when faced with immediate temptations.

According to the *Diagnostic and Statistical Manual of Mental Disorders (DSM-IV)*, a number of addictive disorders are likewise characterized by a persistent desire for self-control (i.e., abstinence from drug use, gambling, etc.) but repeated failures to achieve it. Thus the treatment-seeking addict, like the rest of us, prefers the long-term benefits of forgoing an immediate pleasure at all times except when the temptation becomes immediately available. At that moment he seems to lose his "willpower", he behaves impulsively, and subsequently lives with regret. As Ainslie (1992) has put it – we seem to be of two selves: the *you* of the moment who behaves impulsively, and the *you* of all other times - the *you* who lives with self disappointment.

Because nearly everyone can relate to examples of preference reversals they have been, not surprisingly, frequently documented in the human delay-discounting literature (for a review see Green & Myerson, 2004). Interestingly, the deeply bowed shape of the hyperbolic discounting curve (Equation 2) predicts preference reversals.[3] This is illustrated in Figure 3 which shows hyperbolic discounting functions for two rewards, one twice the objective amount of the other. At time T2 neither reward is immediately available. Assuming individuals choose the reward with the greater discounted value, preference is for the larger-later reward. From the temporal vantage point of T2, removed from the temptations of an immediate reward, one can clearly see the advantages of pursuing a course of "self-control". This is the time at which those expensive mail-order diet meals are purchased. However, at T1 the smaller-sooner reward (e.g., an unexpected box of doughnuts in the break-room) is immediately available whereas the larger-later reward (improved health, physique, etc.) is not. The value of the immediate reward now

exceeds the discounted value of the delayed reward and preference reverses. This simple shift in time from T2 to T1, with no other changes, yields the preference reversal – a "change of mind", a decision that yields regret.

Because preference reversals are predicted by the shape of hyperbolic delay discounting functions, they should be observed in any species which discounts delayed rewards according to Equation 2. Tests with humans (Green & Myerson, 2004), pigeons (e.g., Ainslie & Herrnstein, 1981; Green, Fisher, Perlow, & Sherman, 1981), and rats (Green & Estle, 2003) have supported this prediction; but thus far no other nonhuman species has been tested. It is important to note that exponential discounting can predict preference reversals if the rate of discounting is allowed to vary with reward amount or intensity of the aversive stimulus. While such amount-dependent discounting rates have been observed with humans (e.g., Green et al., 1994), this has not been the case with nonhumans despite several attempts (e.g., Richards, Mitchell, de Wit, & Seiden, 1997). That moving from T1 to T2 in Figure 3 produces preference reversals in animals despite no amount-dependent discounting is a challenge to an exponential discounting equation.

A particularly interesting demonstration of the preference reversal phenomenon was presented by Deluty (1978, Experiment 3). In one condition of this study, rats chose between a 1 sec shock delivered 2 sec into a post-choice feeding period, or a 2 sec shock delivered 12 sec into this feeding period. This is illustrated at time T1 in Figure 4. Here the rat faces a choice between a smaller-sooner and a larger-later shock. Before describing Deluty's results, it is important to note that as values fall below the x-axis in Figure 4, the more aversive is the event (i.e., 2 s of shock is more aversive than 1 s of shock and 2 appears further below the x-axis than 1). At T1, both shocks are delayed and the aversive "values" of both are therefore discounted. Because the smaller-sooner shock retains more of its aversive "value" than the larger-later shock (i.e., the

open data point at T1 is further below the x-axis than the solid data point), Deluty's rats preferred the larger-later shock (an impulsive choice). However, at T2 the hyperbolic discounting functions have crossed paths and now the larger-later shock retains more of its subjective aversive "value". This corresponds well with the rats' choices which shifted in favor of the smaller-sooner shock as the rats moved from T1 to T2. Although the shape of the discounting function describing choices involving losses has been shown to be hyperbolic (Equation 2), whether the two discounting processes are affected the same way by a common set of experimental variables is currently unknown (see Green & Myerson, this volume for evidence that the two may be different processes).

Figure 4 provides a reasonable description of several forms of procrastination. Consider procrastinating the task of signing up for paycheck withdrawals which will be placed in college savings account for your children. If one starts the account now, the amount of money that will have to be put away each month (analogous to the 1 s shock experienced by Deluty's rats) will be small relative to that which will have to be saved each month if you continue to procrastinate (2 s shock). However, at T1 decreasing your salary by the amount saved is subjectively worse than the discounted aversive value of having to save/spend more money in the future. Clever financial advisors have taken a page from the behavioral-economic delay discounting literature (Thaler & Benartzi, 2004) and have asked employees to make choices about their savings at T2. That is, the advisors don't ask the employee to start their savings (and experience a loss of money) now at T1, they ask them to commit to putting a percentage of their next pay raise (a delayed event) into the savings program. From the temporal vantage point of T2 the employee can see that having to save more money in the distant future is worse (solid data point at T2) than

having to save less money a bit sooner. This *Save More Tomorrow* program has significantly increased the number of employees saving for their future and the amount they have saved.

As this simple example illustrates, delay discounting is an important behavioral process, as are the variables that can affect it. Much of the rest of this volume is concerned with these variables, be they genetic, neurochemical, or related to the environmental contingencies of reinforcement and punishment under which the organism's choices are made. To prepare the reader to tackle these chapters, the next section provides an overview of the most commonly used procedures for quantifying delay discounting in animal and human subjects.

Procedures for Assessing Delay Discounting

Several procedures have been used to systematically investigate impulsive decision-making in human and nonhuman subjects. Borrowing from psychophysical research, most use some form of adjusting or titrating procedure to determine indifference points between smaller-sooner and larger-later rewards. Recall that at the indifference point the value of the two rewards is equivalent, thereby providing a measure of the discounted value of the delayed reward. Because the pioneering work in assessing delay discounting was conducted with nonhuman subjects, and because many of the procedures used with humans are derivative of those used with animals, we will begin by examining the most commonly used procedures in the nonhuman delay discounting literature.

Procedures Used with Nonhuman Subjects

Most of the research on delay discounting in nonhumans has been conducted with rats or pigeons pressing levers or pecking keys in operant chambers to obtain immediate or delayed food or liquid reinforcers. The advantages of this general procedure are enormous: automated

presentation of stimuli and rewards, sessions conducted in an environment free of experimenter bias, and automated and temporally precise data collection.

General procedures. Several procedures are common to nearly all of the specific procedures discussed below. The first of these occurs at the beginning of a choice trial when the animal is required to press a lever, peck a key, or engage in some other response that places the animal equidistant from the two choice alternatives. The importance of the centering response is obvious: if the animal selects the alternative on the right simply because it happens to be standing on the right side of the chamber when the trial begins, then the choice tells us nothing about delay discounting.

A second general procedure is the use of forced-choice trials. On these trials, after the centering response is emitted, only one alternative is available and the trial does not end until the animal selects it and experiences the consequences of doing so. Forced-choice trials are designed to expose the animal to both sets of consequences before the free-choice trials in which they are free to select either outcome. To our knowledge, no systematic study has been made of the effects of the ratio of forced- to free-choice trials on choice or the number of sessions required until choice stabilizes.

Most procedures require a single response to register a choice (or a forced-choice) and initiate the reinforcer sequence. Requiring additional responses would add effort and time to the delivery of either reinforcer and might be conceptualized as moving in the direction from T1 to T2 in Figure 3. Finally, an inter-trial interval (ITI) follows reinforcer delivery and it holds constant the time between choice opportunities regardless of which alternative is selected. Consider an experiment in which the larger-later food reward is delayed by 10 s. If the animal chooses the small-immediate alternative, the sequence of responses and reinforcer may be over

in just a few seconds. If the next trial is started immediately (no ITI), the animal would do well to repeatedly choose the smaller-sooner reinforcer as it would increase the local reinforcement rate relative to the time required to obtain a delayed reinforcer; hardly an appropriate model of impulsivity. With an ITI, selecting the smaller-sooner reinforcer yields a lower local and overall rate of reinforcement than that which could be obtained by selecting the larger-later alternative.

Adjusting-delay procedure. One of the first procedures used to assess rates of temporal discounting was pioneered by Mazur (1987). In this procedure the subject chooses between a large food-reward delivered following an adjusting delay vs. a smaller amount of food delivered after a fixed delay. The procedure is designed to identify the delay at which the subject is indifferent between the two rewards. Recall that the indifference point provides the measure of the degree of delay discounting. In the adjusting-delay procedure that measure is the delay to the larger-later alternative which might be thought of as the longest delay the subject will tolerate before preferences shifts toward the smaller-sooner reward. Thus, if the adjusted delay is brief when stable indifference is achieved, this is indicative of more extreme delay discounting.

In a typical adjusting-delay procedure, subjects complete two forced-choice trials (exposure to both consequences) followed by two free-choice trials. If the smaller-sooner reward is selected on both free-choice trials, indifference has not been obtained so the non-preferred outcome is made more enticing by decreasing the delay to the larger-later reward (usually by 1 s) in the next block of forced- and free-choice trials. Likewise, if the subject consistently chooses the larger-later reward on the free-choice trials, the delay to the larger-later reward is increased in the next trial block.

In the abstract this procedure would result in an adjusted delay to the larger-later reward at which the subject was consistently indifferent. In reality, the delays are widely adjusted (by

the subject's choices) up and down at first as the subjects are relatively insensitive to the changing delays. With continued experience, however, the range across which delays are adjusted is constrained and a quantitative stability criterion may be met (see Mazur, 1987). Once stability is achieved, the mean adjusted-delay (MAD) obtained over the stable sessions serves as the indifference point. When this process is repeated across several fixed delay values, MAD's are plotted as a function of the fixed delay to the smaller-sooner reward. Because Equations 1 and 2 make different predictions about the characteristics of this function, deviations from these predictions can be used to support one or the other equation. Mazur (1987) found that the hyperbolic discounting function (Equation 2) provided the most accurate description of his pigeons' choices and as noted above, this finding has been frequently replicated.

Concerns about the adjusting-delay procedure were raised by Cardinal, Daw, Robbins, and Everitt (2002) who reported that despite completing thousands of forced- and free-choice trials, most of their rats failed to reach a constrained range of adjusted delays from which indifference points could be derived. Unfortunately, studies designed to identify procedural variables responsible for the discrepancy between the Cardinal et al. findings and those from several other laboratories have not been conducted. One difference that might warrant investigation is the rate at which delays are adjusted across laboratories. Cardinal et al. adjusted by 20-30% (range: 0.4-9 s) while other laboratories adjust in 1 s increments. Adjusting more rapidly may yield unstable indifference points if the rat's behavior requires more exposure than a single block of trials to be affected by the change in delay.

Adjusting-amount procedure. The adjusting-amount procedure pioneered by Richards et al. (1997) is similar to the adjusting-delay procedure. Both use the subject's choices to titrate a characteristic of one of the reinforcers (in this case the amount of the smaller-sooner reinforcer)

until a stable indifference point is attained. In the experiments conducted by Richards and his colleagues water-deprived rats chose between a small amount of water (10 μl) delivered following a fixed delay and an even smaller amount of water delivered immediately. If the fixed alternative is selected, then the smaller-sooner amount is increased by some percentage (typically a 10-15% increase). If the subject chooses the fixed-delay alternative on two consecutive trials, then it completes a forced-choice trial on the adjusting-amount alternative on the next trial. The opposite adjustment is made if the subject chooses the adjusting amount alternative. The adjusted amount at the indifference point provides an easily interpreted discounted value of the delayed reinforcer.

Some researchers have used the adjusting-amount procedure to assess indifference points at several different delays to the larger-later reinforcer. In the original Richards et al. (1997) study, for example, five different delays were assessed in five-day blocks, for a period of 75 days (15 days per delay). The resulting indifference points may be plotted against the fixed delays as in Figure 2. These indifference points may then be fit with one of the nonlinear discounting equations discussed above, using standard regression techniques.

Green et al. (2007) evaluated if the adjusting delay and adjusting amount procedures yield the same discounting rates (k in Equation 2). In two experiments they demonstrated convincingly that these procedures yield the same estimates of discounting and they extended the use of the adjusting amount procedure to a new species (pigeons) and a new reinforcer type (food pellets). They also reported that the number of sessions required to obtain stable indifference points was approximately the same across the adjusting amount (22 sessions) and adjusting delay (24 sessions) procedures.

Some researchers have adapted the adjusting-amount procedure for the purposes of studying the effects of pharmacological manipulations or neurological lesions on delay discounting (e.g., Acheson et al., 2006). In these studies amounts are adjusted as above but the delay to the larger-later reinforcer remains unchanged across sessions until the indifference point stabilizes. This provides a baseline against which the effects of these acute or chronic manipulations may be judged.

Evenden & Ryan procedure. Perhaps the most widely used procedure to quantify impulsive choice in nonhumans is the one developed by Evenden and Ryan (1996). This procedure is frequently used because it provides measures of sensitivity to reinforcer amount and reinforcer delay in each session and, when these measures stabilize across days, the procedure yields an ideal baseline from which to evaluate the effects of acute and chronic manipulations (e.g., drug injections or neurological lesions) on sensitivity to amount and sensitivity to a range of delays.

Under the Evenden and Ryan procedure each session is composed of five 8-trial blocks. Within each block the first two trials are forced-choice trials (one on each alternative) and the remaining six are free-choice trials. At each free-choice trial the subject chooses between a smaller-sooner (e.g., 1 pellet now) and a larger-later reward (e.g., 3 pellets in 10 s). Across the five 8-trial blocks, the delay to the larger reward is systematically increased; typically from 0 s in the first block up to 60 s in the last block. Thus, the first trial block provides at least a gross measure of sensitivity to differences in reward amount (% choice of the larger reward) and the subsequent trial blocks provide a measure of sensitivity to progressively increasing delays (% choice of the larger-later reward in each block).

While there are several advantages of the Evenden and Ryan procedure, it is not without its drawbacks. First, stable choice between two non-identical non-adjusting outcomes arranged in a discrete-trial format (like that used in the Evenden & Ryan procedure) should result in exclusive preference for the higher-valued alternative (e.g., Herrnstein, 1981); however, exclusive choice is not typically reported outside the first (no-delay) trial block. This may be due to across-subject averaging of exclusive preferences, although the few studies that have provided individual subject data (e.g., Evenden & Ryan, 1999) and our own experiences with this procedure suggest this is not the case. Another possibility is that choice in each trial block is affected by carry-over effects from prior sessions or prior trials blocks within the same session. Evidence suggesting a carry-over effect was reported by Fox, Hand, and Reilly (2008) who found that stable choice percentages obtained with the Evenden and Ryan procedure were influenced by delays in preceding trial blocks. When delays started at zero and increased in subsequent trial blocks, percent choice of the larger-later reward was significantly higher than in a separate condition in which delays decreased across trial blocks. These within-session carry-over effects are particularly problematic if one is interested in measuring steady-state impulsive choice as was the case in the Fox et al. study designed to explore impulsivity differences across strains of rats.

A second, related, drawback is that choice of the larger reinforcer in the no-delay trial block (typically the first trial block) often is not exclusively for the larger reward (e.g., Cardinal, Robbins, & Everitt, 2000; Cardinal, Pennicott, Sugathapala, Robbins, & Everitt, 2001). This suggests that under the Evenden and Ryan procedure avoidance of the delayed-reward lever during the latter portions of the preceding session carries over into the no-delay trial block of the

present session. This is problematic because choice in the no-delay trial block is a putative measure of sensitivity to reinforcer amount.

A third drawback is specific to studies examining effects of drugs or neurological lesions on impulsive choice. A not uncommon outcome of these manipulations is that the entire choice function shifts upward (e.g., van Gaalen, van Koten, Schoffelmeer, & Vanderschuren, 2005), downward (e.g., Evenden & Ryan, 1999) or shifts toward indifference (e.g., Uslaner & Robinson, 2006) which makes interpretation of the effect difficult. Evenden and Ryan (1999), for example, reported that 1.0 g/kg ethanol shifted the entire choice function downward in all trial blocks. Because preference for the larger reinforcer in the no-delay trial block declined, ethanol would appear to decrease sensitivity to reinforcer amount but another possibility is that the enhanced sensitivity to reinforcer delay observed in the other trial blocks carried-over into the no-delay trial block.

Procedural improvements would appear to be warranted. One potential improvement was actually used by Evenden and Ryan (1996) but has appeared infrequently in the literature since. In addition to the usual procedures, control sessions are periodically conducted in which no delay is arranged to the larger reinforcer in any trial block. Such control sessions may enhance sensitivity to changing delays when they are scheduled. Another potential improvement is to increase the number of forced-choice trials within each trial block. This might be accomplished by dropping the trial block in which a 60 s delay to reinforcement is typically scheduled (steady-state assessments of impulsivity reveal that most rats will not tolerate delay > 30 s). More generally, any procedural modification designed to increase the salience of the particular delay in operation within a trial block should yield a better measure of sensitivity to that delay. Given

how frequently the Evenden and Ryan procedure has been used, systematic investigation of these or other procedural improvements is warranted.

Other procedures. Two other procedures are worth brief mention. The first is the T-maze procedure in which a rat is released from a start box and runs to the end of one of two goal arms; one baited with food available upon arrival, the other associated with a larger food reward delivered following a delay (e.g., Thiébot, Le Bihan, Soubrié, & Simon, 1985). The increased labor to the experimenter, relative to the automated operant chamber, may be responsible for the infrequent use of this procedure but another problem is that the procedure confounds delay with the effort required to run to the goal box; thereby making it difficult to determine if one is measuring delay or effort discounting (or both).

The second infrequently used procedure is to give monkeys a choice between two visually available rewards, the larger of the two delivered following a delay (e.g., Rosati, Stevens, Hare, & Hauser, 2007). Although rich in face validity, interpreting the results of these studies is difficult. Monkeys rarely choose a visually smaller reward even when selecting it results in a larger reward than would have been obtained had they chosen the visually larger one (e.g., Boysen & Berntson, 1995). A superior practice is to have the monkey select a choice lever with no rewards visually associated with either one (e.g., Woolverton, Myerson, & Green, 2007).

Procedures used with Humans

Hypothetical outcomes. The most widely used procedures for assessing degree of delay discounting in humans are derived from those pioneered by Rachlin, Raineri, and Cross (1991). In this study, participants were asked to choose between $1,000 now and $1,000 given after delays ranging from 1 month to 50 years; all rewards were hypothetical. When the reward amounts were equal but one was delayed, participants generally preferred to receive $1,000 now.

At each delay, Rachlin et al. used an adjusting-amount procedure whereby they gradually decreased the amount of money available now (e.g., $990 now vs. $1000 in one month) until participants were choosing between $1 now and $1000 following the delay. The procedure was repeated in reverse order at each delay and the indifference point was given by the average amount of the immediate reward at the point at which the participant no longer preferred the immediate reward (amounts adjusted downward) and no longer preferred the delayed reward (adjusted upward). All told, the delay discounting assessment yielded seven indifference points which could be plotted as in Figure 2.

The Rachlin et al. (1991) data were compelling not only because they quickly yielded orderly estimates of delay discounting but because their human participants' discounting function was well described by the hyperbolic discounting equation (Equation 2) which had proven most successful in describing nonhuman choice (e.g., Mazur, 1987). Subsequent experiments employing hypothetical outcomes and different reward amounts replicated this finding both at the level of group averages and individual participants (e.g., Kirby & Maraković, 1995; Green, Myerson, & McFadden, 1997; Myerson & Green, 1995). While these findings provided evidence for inter-species continuity of the process by which delayed outcomes were discounted, concerns about the hypothetical nature of the rewards were frequently raised (e.g., Bickel & Marsch, 2001; Kirby & Maraković).

Real outcomes. Concerns about using purely hypothetical rewards led some researchers to instruct their participants that there was a chance that one of their choices would have real outcomes at the end of the session. In theory, this should increase the probability that participants would make all choices as though the outcomes were real. Comparisons between this procedure and one in which all rewards were purely hypothetical revealed no differences in rate of delay

discounting (Johnson & Bickel, 2002; Madden et al., 2003). Subsequent studies that further increased the proportion of real rewards also failed to show a difference in degree of delay discounting between real and hypothetical rewards (Lagorio & Madden, 2005; Madden et al., 2004). In addition, these studies showed that whether rewards were real, potentially real, or hypothetical, the form of the discounting curve was hyperbolic (Equation 2).

Nonetheless, a problem remained. Experiments designed to detect the effects of acute doses of drugs of abuse on delay discounting were failing to reveal expected effects when hypothetical or potentially real rewards were arranged (e.g., Richards, Zhang, Mitchell, & de Wit, 1999). These findings likely played a motivational role in the development of the *experiential discounting task* (EDT; Reynolds & Shiffbauer, 2004). In the EDT, participants choose between a delayed, probabilistic monetary reward (e.g., a 35% chance of receiving $0.30) and an immediate, assured reward (e.g., 100% chance of obtaining $0.15). If the smaller-sooner-sure-thing is selected, the amount of that reward is decreased on subsequent trials and this process is repeated until an indifferent point is reached. An apparent benefit of the EDT has been that state manipulations such as sleep deprivation (Reynolds & Shiffbauer) and alcohol consumption (Reynolds, Richards, & de Wit, 2006) have been shown to increase impulsive decision making.

Unfortunately, procedural problems with the EDT make it difficult to interpret why these manipulations have increased impulsivity. First, the procedure confounds delay and probability because the larger-later reward is delivered probabilistically. Although EDT analyses of delay discounting normalize indifference points as a percentage of the discounted value of the large-immediate-probabilistic reward, little is known about the interaction between probability and delay as one or the other is manipulated (although see Yi, de la Piedad, & Bickel, 2006). A

second, more serious, problem with the EDT is that participants often forgo the larger-later reward at very short delays (e.g., 1 min or less) whereas previous research with humans suggests participants should strongly prefer the larger-later reward even at much longer delays (e.g., Logue, Peňa-Correal, Rodriguez, & Kabela, 1986). Some of this difference may result from the probabilistic nature of the delayed reward but another factor appears to be that the EDT does not include a post-consequence ITI which holds constant the time between choice-opportunities regardless of the alternative selected. Thus, choosing the smaller-sooner outcome increases local rate of reinforcement in the EDT and more quickly ends the portion of the experiment in which participants are required to pay attention; two outcomes that might better be described as "maximizing" than "impulsivity" (Logue et al.), particularly for sleep-deprived or alcohol-intoxicated participants. Scheres et al. (2006) demonstrated the importance of an ITI to choices made in a modified EDT (delayed rewards were not probabilistic). They reported that participants made significantly fewer impulsive choices when an ITI was included than when it was not (see also Flora, 1995). Such findings raise questions about the EDT in studying the effects of pharmacological manipulations on impulsivity or delay discounting.

Other procedures. Two variations on the procedures outlined above are used commonly, yield indifference points rapidly, and broadly concord with those widely reported in the literature. The first is a class of titrating procedures that use a participant's prior choices to exclude from subsequent presentation any choice alternatives falling outside the range in which the participant's indifference point might fall (e.g., Johnson & Bickel, 2002; Richards et al., 1999). For example, if the participant has twice indicated that she would prefer $500 now over $1,000 in 5 years, then one may assume that she would also prefer >$500 now over $1,000 in 5 years and there is no utility in asking him/her these questions. Randomizing the choice

alternatives presented, rather than honing in linearly on the indifference point, yields hyperbolic discounting functions in approximately 15 min. A second, even more rapid, procedure involves participants make a handful of choices from which an estimate of the discounting rate may be interpolated from the pattern of choices. This procedure has proven useful in examining population differences in delay discounting (e.g., Kirby, Petry, & Bickel, 1999). Caution is warranted when comparing discounting rates across studies using different assessment procedures. While all of the procedures outlined above appear equally capable of differentiating populations such as drug-dependent participants vs. controls, several studies have shown that different procedures yield systematic and statistically significant differences in estimates of discounting rate (e.g., Epstein, et al., 2003).

Summary and Future Directions

Discounting the future is a behavioral process common to every species that has been tested thus far. The procedures employed across species and laboratories have varied considerably but they all suggest that as delays increase the value of an outcome decays according to a hyperbolic function. New discounting equations informed by computational modeling and neuroscience findings have been recently formulated and these will no-doubt lead to productive research lines (e.g., Redish & Kurth-Nelson, this volume). New equations or old, they have in common a deeply bowed discounting function that deviates systematically from the exponential function predicted by normative economic theory. This deviation is “irrational” in the sense that we change our minds from choosing what is best for us in the long run to choosing what is best for us now. We all succumb to this temptation. We all behave irrationally; though some more than others.

Perhaps owing to the latter difference in the degree to which the future is discounted by

different populations of humans (e.g., individuals diagnosed with addictive disorders), the last 10 years have seen a proliferation of empirical papers published on the topic of delay discounting. As illustrated in the remainder of this book, this research has yielded important findings which provide hints about the likely areas of fruitful research over the next 10 years. Future progress in the study of delay discounting will depend, we believe, on procedural improvements in both the human and animal laboratories. In the animal laboratory, new techniques for simultaneously assessing sensitivity to amount and delay within a single session are needed for purposes of detecting effects of acute experimental manipulations (e.g., Ho et al., 1999). In the human laboratory, existing procedures have proven adequate for discriminating between populations but inadequate for detecting effects of some experimental manipulations. Improvements on the EDT such as using real delays to real *consumable* non-probabilistic rewards may hold the key. Ironically, time will tell.

Footnotes

1. An unfortunate linguistic convention is to attribute causation to patterns of behavior such as the pattern quantified by a discounting rate (*k*). However, it is important not to reify delay discounting rate as a causal object when it is simply a quantitative description of a pattern of choices. Thus, a high discounting rate does not cause impulsive choice, it is derived from impulsive choices. Causes of discounting rates are to be found in genetic, experiential, and neuro-chemical variables.
2. Future comparisons of the hyperbolic and hyperbola-like equations might usefully be informed by the use of an information criterion such as the Akaike or Bayesian criteria (see Burnham & Anderson, 1998). These criteria are useful when determining the merits of additional free parameters in mathematical models of behavior.
3. In this instance we use the term *predicts* because they hyperbolic shape of the discounting function has been observed so many times and in so many species that one can predict this form and the preference reversals that are implicated by the form.

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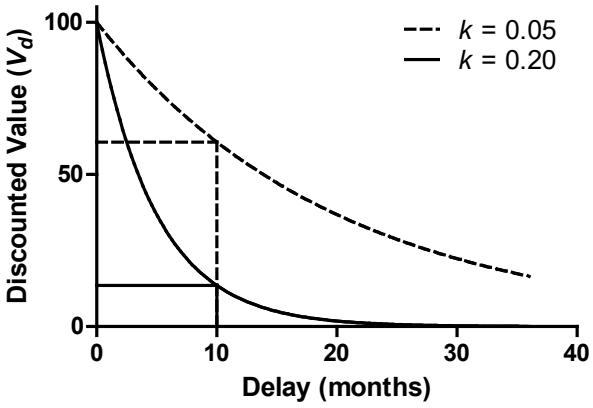

Figure 1. Value discounted exponentially at high (solid line) and modest (dashed line) rates. Y-axis values of the horizontal lines intersecting with the discounting functions indicates the present (discounted) value of the reward when delayed by 10 months.

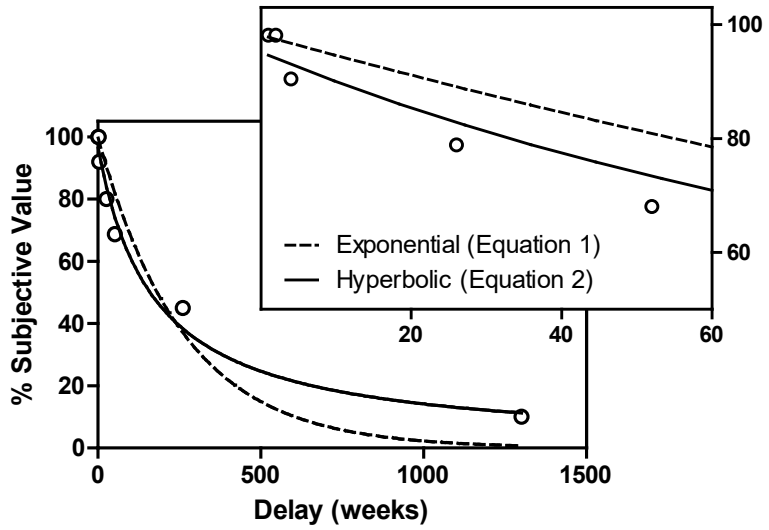

Figure 2. Exponential and hyperbolic discounting curves fit to average indifference points of X non-drug-using control participants in the study conducted by Madden et al. (1997). In inset panel expands the 1 day to 52 week range of delays so that the fits provided by the two equations can be more easily compared.

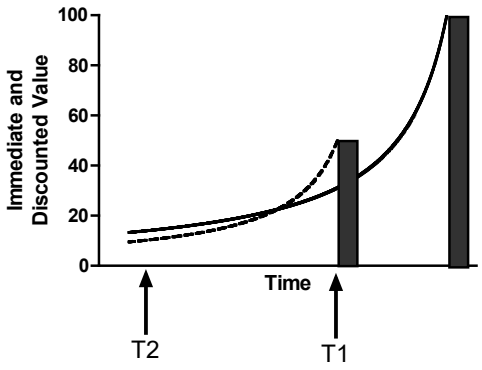

Figure 3. Hyperbolic discount functions fit to smaller-sooner and larger-later rewards. The same rate of delay discounting (*k*) was used to fit both curves. At T1, the smaller-sooner outcome is available immediately while the larger-later reward is not. Moving from T1 to T2 (both rewards delayed), the discounting functions cross yielding a reversal in preference.

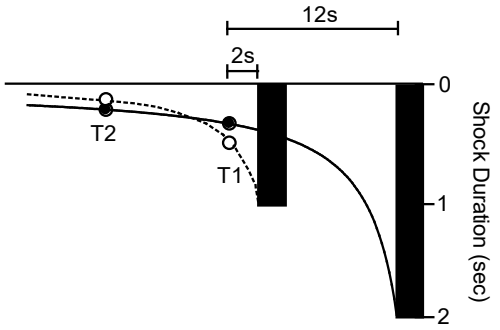

Figure 4. Discounting of delayed aversive consequences; modeled after the choice alternatives arranged by Deluty (1978, Exp. 3). See text for details.