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Delay-discounting probabilistic rewards: Rates decrease as amounts increase

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The independence of delay-discounting rate and monetary reward size was tested by offering subjects ($N = 621$) a series of choices between immediate rewards and larger, delayed rewards. In contrast to previous studies, in which hypothetical rewards have typically been employed, subjects in the present study were entered into a lottery in which they had a chance of actually receiving one of their choices. The delayed rewards were grouped into small ($30–$35), medium ($55–$65), and large amounts ($70–$85). Using a novel parameter estimation procedure, we estimated discounting rates for all three reward sizes for each subject on the basis of his/her pattern of choices. The data indicated that the discounting rate is a decreasing function of the size of the delayed reward ($p < .0001$), whether hyperbolic or exponential discounting functions are assumed. In addition, a reliable gender difference was found ($p = .005$), with males discounting at higher rates than females, on average.

The present value of a reward decreases as the delay to that reward increases. For example, one typically would choose to receive $10 now over $10 tomorrow, $10 tomorrow over $10 in 2 days, and so on. This decrease as a function of delay is called *delay-discounting*, and the general rule can be stated succinctly: *the sooner, the better.* Delay-discounting is of interest in its own right, as a psychophysical function with implications for models of human and animal choice (see e.g., Benzion, Rapoport, & Yagil, 1989; Herrnstein, 1981; Logue, 1988; Rachlin, 1992; Stevenson, 1986, 1993), and because it has potential to provide an account of impulsiveness (Ainslie, 1975, 1992; Rachlin & Green, 1972). The success of discounting models of impulsiveness hinges on the possibility of a reversal of preference for a larger, more delayed reward (say, finishing a paper by a deadline at week's end) to preference for a smaller, earlier reward (say, watching a movie tonight) as both rewards approach in time. Although I presently express a preference for finishing the paper, as the movie looms closer my preference may reverse, leading to an impulsive choice to watch the movie—the paper be damned.

Such preference reversal cannot occur when the discounting rate is constant across delays and reward amounts, as is assumed by normative economic models (e.g., Loewenstein, 1992; Samuelson, 1937; Strotz, 1955). Constant-rate discounting is exponential in form, and may be described by the following equation:

$$V = Ae^{-kD}, \tag{1}$$

where V is the present value of the delayed reward, A is the amount of the delayed reward, D is the delay, and k is the discounting rate parameter. Under such a model two future rewards separated by a fixed difference in delay should maintain a constant ratio in their present values—a reward that is preferred at any delay should be preferred at all delays.

An alternative form of discounting in which the discounting rate is not constant across delays is provided by the hyperbolic function (Mazur, 1987),

$$V = \frac{A}{1 + kD}. \tag{2}$$

Hyperbolic discounting predicts preference reversals as a function of time, as required by discounting models of impulsiveness: The hyperbolic functions are steeper at small delays and flatter at long delays than the exponential, which allows hyperbolic curves to cross. Such preference reversals have been documented with real rewards for pigeons (Ainslie, 1974; Green, Fisher, Perlow, & Sherman, 1981; Rachlin & Green, 1972) and people (Kirby & Herrnstein, 1995), providing evidence against normative exponential discounting.

However, Green and his colleagues (Green et al., 1981; Green, Fristoe, & Myerson, 1994; Green & Myerson, 1993; and see Thaler & Shefrin, 1981) have pointed out that, if the discounting rate parameter varies inversely with amount, exponential discounting functions can also predict preference reversals. A larger, later reward with a low exponential discount rate could be preferred to a smaller, earlier reward with a higher exponential discount rate when the delays to both rewards are large, but preference could reverse to the smaller reward as the delays to both rewards decrease. (Note that this type of exponential discounting still would not satisfy the normative model precisely *because* it predicts preference reversals.) Thus, most arguments against exponential discounting have tacitly assumed that the discounting rate parameter is independent of amount. The purpose of

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the present study was to investigate the validity of this assumption by using a novel parameter estimation procedure. Each subject is assigned to the discounting rate parameter that yields the highest consistency among the subject's choices over a fixed set of trials. Rather than attempting to distinguish between hyperbolic and exponential functions, we instead employed trials that allowed us to determine whether the assigned discounting rate parameters varied inversely with amount without presupposing either functional form.

The present study also provides a methodological alternative to the three methods used in previous studies in which evidence has been found for an inverse relationship between discounting rate and amount. These methods are: (1) having an experimenter individually offer each subject a series of choices while varying reward delays on the basis of the subject's choices (Green, Fristoe, & Myerson, 1994; Raineri & Rachlin, 1993); (2) having an experimenter individually offer each subject a series of choices between rewards at predetermined delays (Green, Fry, & Myerson, 1994); and (3) using a questionnaire to ask subjects to estimate the present value of a series of delayed rewards (Benzion et al., 1989; Thaler, 1981). In the present study we combined aspects of the second and third of these procedures: Subjects made a series of choices between rewards at predetermined delays, with trials presented in a questionnaire format. This method allowed many choices to be offered to a large number of subjects.

In addition, in each of these previous studies, subjects were offered strictly hypothetical choices (see, e.g., Benzion et al., 1989; Green, Fristoe, & Myerson, 1994; Green, Fry, & Myerson, 1994; Raineri & Rachlin, 1993; Thaler, 1981). It is important to begin to determine whether results based on hypothetical rewards will generalize to choices that could have real consequences. Thus, we offered subjects a chance of receiving one of their choices. Two subjects were chosen at random to receive the alternative they chose on one of the trials, and subjects were instructed to make each choice as though it were the one they would receive.

Finally, perhaps the most important differences between this study and previous work are that we estimated the rate/amount relationship as a within-subject effect and that we assess the consistency of each subject's choices with that subject's estimated discounting rates. Discounting rates were estimated separately for each of three reward sizes for each subject, because it is important to show that the inverse rate/amount relationship is not an artifact of averaging over subjects. Subjects' choices were very consistent across all reward levels, and the results provide strong evidence that discounting rate is inversely related to amount.

METHOD

Subjects

The choice questionnaire was distributed via campus mail to all of the approximately 2,000 Williams College undergraduates, 672 of whom voluntarily returned the questionnaires in exchange for entrance into a drawing for a monetary reward of up to \$85 based on a random selection of one of their choices. Fifty-one of these subjects (7.6%) misunderstood the instructions and circled a single trial on the entire questionnaire rather than circling one alternative on each trial. The results below are for the remaining 621 subjects: 318 women and 303 men. The questionnaires requested a phone number for the purpose of notifying the winners of the drawing, but were otherwise anonymous.

Materials

The questionnaire consisted of instructions, 21 choice trials, and five demographic questions (gender, college year, age, handedness, and date of birth). The 21 choice trials are shown in Table 1. Each choice trial consisted of one smaller, immediate reward and one larger, delayed reward. For each pair of alternatives, one may calculate the value of the discounting rate parameter for which the discounted value of the delayed reward is equal to the immediate reward. These discounting rate parameters are shown for each trial in Table 1. For example, a subject who is indifferent between \$34 tonight and \$35 in 43 days discounts value with a rate parameter of 0.0007, as shown in the first row of Table 1. (Because the "immediate" rewards would be obtained the night that the subject returned the questionnaire, they were actually delayed by a few hours. However, little discounting would occur at the observed rates over this interval, so the effect of treating this delay as zero would be to bias the estimated discounting rates upward negligibly from those shown in Table 1.)

The amounts and delays were chosen so that hyperbolic and exponential discounting would yield nearly identical orderings of the trials in the degree of impulsiveness required to produce selections of the immediate reward. This was done so that any observed amount/rate relationship would not presuppose one of the two functions. As shown in the next-to-last column of Table 1, the 21 trials fall roughly into seven parameter sizes, with virtually the same rank ordering whether one uses hyperbolic or exponential functions. As one moves down the table, one can see that choices of the immediate reward correspond to increasingly higher discount rates, and therefore, to increasingly higher impulsiveness: As the parameter value at indifference increases, a more impulsive subject is required to choose the immediate reward. Within ranks, the choice trials in Table 1 are shown in order of increasing delayed reward size. The trials were presented in the same randomized order on all questionnaires, and the actual order of trials on the questionnaire is given in the leftmost column of Table 1.

Finally, the delayed rewards were chosen so that they fell into groups of seven small (\$30–\$35), seven medium (\$55–\$65), and seven large (\$70–\$85) reward sizes. (Identical amounts were not used so that it would be more difficult for a subject to establish a single decision rule for any given delayed reward size, which could artificially increase consistency.) The seven delayed rewards of each size were spread nearly evenly across the seven ranges of discounting parameter values so that subjects' choices would allow us to estimate the parameter values for each reward size with roughly the same degree of precision.

Procedure

The instructions described the nature of the task and the drawing, and encouraged subjects to regard each trial as though it were the only choice they faced: "To make sure that you get a reward you prefer, you should *assume* that you are the winner, and then make *each choice* as though it were the one you will win." The instructions further explained that the questionnaire could be returned on either of 2 successive days, and that a separate drawing would be held each day. The subjects were not told that the questionnaire was distributed to all students, nor were they told the number of likely participants. Because of the manner in which the questionnaires were distributed and returned, subjects were free to take as long as they wished in filling out the questionnaire (although virtually all of the subjects that we observed filled out the questionnaire and returned it before leaving the campus mailroom). This procedure also made it impossible for us to prevent collusion.

On 2 successive days, 1 subject's questionnaire was selected by a random number generator from all questionnaires that were returned that day, and one of the trials on that subject's questionnaire was chosen at random as the reward. On the first day, the winner chose the immediate reward on the winning trial and was paid \$34 on the night of

Table 1
Choice Trials and Their Associated Discounting Parameter Values

Order	Choice Trial	Hyperbolic	Exponential	Rank	%Ss
4.	$34 tonight or $35 in 43 days	0.0007	0.0007	1	12
15.	$53 tonight or $55 in 55 days	0.0007	0.0007	1	12
7.	$83 tonight or $85 in 35 days	0.0007	0.0007	1	12
20.	$27 tonight or $30 in 35 days	0.0032	0.0030	2	17
9.	$48 tonight or $55 in 45 days	0.0032	0.0030	2	34
12.	$65 tonight or $75 in 50 days	0.0031	0.0029	2	44
8.	$21 tonight or $30 in 75 days	0.0057	0.0048	3	36
16.	$47 tonight or $60 in 50 days	0.0055	0.0049	3	57
14.	$30 tonight or $35 in 20 days	0.0083	0.0077	4	44
10.	$40 tonight or $65 in 70 days	0.0089	0.0069	4	67
3.	$67 tonight or $85 in 35 days	0.0077	0.0068	4	70
18.	$50 tonight or $80 in 70 days	0.0086	0.0068	4	74
11.	$25 tonight or $35 in 25 days	0.0160	0.0135	5	68
2.	$40 tonight or $55 in 25 days	0.0150	0.0127	5	71
19.	$45 tonight or $70 in 35 days	0.0159	0.0126	5	90
21.	$16 tonight or $30 in 35 days	0.0250	0.0180	6	86
6.	$32 tonight or $55 in 20 days	0.0359	0.0271	6	94
17.	$40 tonight or $70 in 20 days	0.0375	0.0280	6	97
5.	$15 tonight or $35 in 10 days	0.1333	0.0847	7	99
13.	$24 tonight or $55 in 10 days	0.1292	0.0829	7	99
1.	$30 tonight or $85 in 14 days	0.1310	0.0744	7	99

Note—The exponential and hyperbolic discounting parameter values are those values at which the immediate and delayed rewards are of equal value according to Equations 1 and 2, respectively. With either the hyperbolic or exponential values, trials can be grouped into roughly seven impulsiveness ranks as shown in the next-to-last column. Trials are shown in increasing order of discounting rank, with trials within ranks in increasing order of delayed reward size. Trial numbers in the left margin show the order of trials on the questionnaire. The last column shows the percentages of subjects choosing the delayed reward on each trial.

the drawing. On the second day, the winner chose the delayed reward on the winning trial and was paid $60 50 days later.

Parameter Estimation Procedure

The 21 choice trials define 20 bounded ranges of discounting parameter values. For example, a subject who chooses the immediate reward on the top three trials in Table 1 and the delayed reward from the fourth trial on down has a parameter value (hyperbolic or exponential) between roughly 0.0007 and 0.003. (All rates below are for delays measured in days.) A more impulsive subject who chooses the immediate reward on the top 18 trials and the delayed reward on the bottom 3 has a hyperbolic parameter value between roughly 0.04 and 0.13 or an exponential parameter between 0.03 and 0.07. Based on the subject's choices of the immediate reward across trials, we assigned each subject a parameter value corresponding to the geometric midpoint of one of the 20 ranges. (The geometric midpoint was used to avoid underweighting the smaller of the two parameters.)

Because subjects' choices are not always perfectly consistent with any single parameter value, the parameter assignments could not be made by simply looking for a switch from the immediate to the delayed rewards moving down the trials in Table 1. Instead, subjects were assigned to impulsiveness ranges that yielded the highest proportion of choices consistent with those predicted by both hyperbolic and exponential discounting functions (which yielded virtually identical consistency measures). For each subject we computed the proportion of choices that were consistent with assignment to each of the 22 impulsiveness ranges (including unbounded), and the subject was assigned to the range that yielded the highest consistency. In the rare cases for which two or more ranges yielded equal consistency, the subject was assigned to the geometric midpoint of those ranges. This consistency measure is conservative in that it weights inconsistent choices near the subject's indifference point equally with inconsistent choices far from the subject's indifference point.

Finally, the trials were grouped into three delayed reward sizes, as described above, and the parameter estimation procedure was repeated within each size. In this way, each subject was assigned a parameter value for small, medium, and large delayed rewards. These values were used to test the hypothesis that parameter values are independent of amount.

RESULTS

Sixty-five subjects either always chose the immediate reward (n = 4) or always chose the delayed reward (n = 61). An additional 28 subjects chose the immediate reward (n = 2) or delayed reward (n = 26) for all trials within at least one of the delayed reward sizes. Therefore, these subjects could not be assigned to a bounded range of parameter values for all three delayed reward sizes. The following results are for the remaining 528 subjects.

Averaged across all reward sizes, the geometric mean and median parameter values were both 0.007 (hyperbolic or exponential). This value indicates that the median subject "switched" from choosing the immediate reward to choosing the delayed reward roughly between the eighth and ninth trials from the top in Table 1. (The percentage of subjects choosing the delayed reward on each trial is shown in the last column of Table 1.) Furthermore, subjects were very consistent in their choices, with an average of 92% of choices consistent with the overall parameter value to which they were assigned. This corresponds to an average of fewer than two inconsistent choices out of the 21 trials. Therefore, the assignment procedure appears to give a good approximation of subjects' underlying discounting rates. The hyperbolic and exponential functions yielded virtually identical results and parameter values, so for simplicity, summary statistics are presented below only for the hyperbolic functions.

A repeated measures analysis of variance was performed on the natural log of the parameter values, with the three delayed reward size groups constituting the within-subject factor, and gender included as a blocking variable. (The natural log is a normalizing transformation for variables with very high ratios of their highest to lowest values.) The geometric mean parameter values were 0.0113, 0.0066, and 0.0047, for the small, medium, and large delayed reward sizes, respectively. All pairwise differences were highly reliable, and the linear decrease in parameter value with mean delayed reward size was also highly reliable [$F(1,526) = 950, p < .0001, r = .80$]. (In the last column of Table 1, one can see that the percentage of subjects selecting the delayed reward increases with delayed reward size within each of the seven discounting ranks.) Interestingly, the nonlinear trend was also reliable [$F(1,526) = 5.9, p = .02, r = .11$], indicating that the decrease in discount rates itself decreases as amounts increase.

Males had an average parameter value of 0.0079, whereas females had a lower value of 0.0063; the difference was reliable [$F(1,526) = 8.0$, $p = .005$, $r = .12$]. Furthermore, the linear decrease in log parameter value with delayed reward amount was slightly but reliably steeper for females than for males [$F(1,526) = 8.9, p = .003$, $r = .13$]. These means are shown in Figure 1. The nonlinear trend in amount did not differ between genders [$F(1,526) = 0.37, p > .50$].

Mean consistencies were 98.7%, 98.2%, and 98.5%, for the small, medium, and large delayed reward conditions, respectively. Differences in consistency were assessed with the same repeated measures design as was used for the parameter values, but no significant differences were found. (The consistency measure was normalized via an angular transformation for binomial proportions). However, the mean consistency with separate parameters for the three delayed rewards sizes (98.5%) was reliably higher than the overall consistency with a single parameter value (92%) [$t(527) = 33.6, p < .0001$].

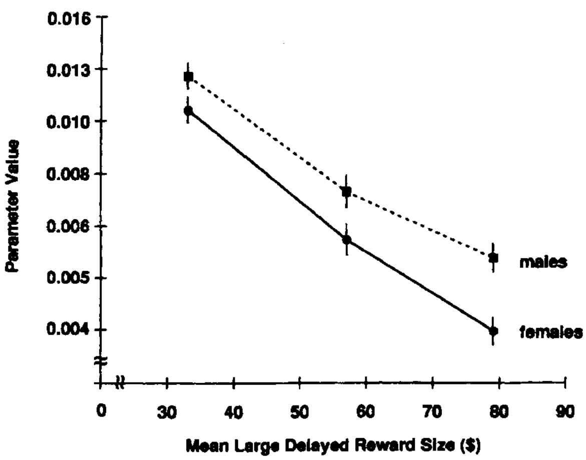

Figure 1. Mean hyperbolic parameter value (k in Equation 2) in $\log_{10}$ coordinates as a function of delayed reward size for males and females. The vertical bars extend 1 standard error of the mean above and below the means.

DISCUSSION

With a new parameter estimation procedure, the results of this study replicated the results obtained in previous studies that discounting rates decrease as the amount of the delayed reward increases (Benzion et al., 1989; Green, Fristoe, & Myerson, 1994; Green, Fry, & Myerson, 1994; Raineri & Rachlin, 1993; Thaler, 1981). The mean hyperbolic discounting parameter values for the small ($30–$35), medium ($55–$65), and large ($70–$85) delayed reward sizes were 0.0113, 0.0066, and 0.0047, respectively. Although the differences may appear to be small, when translated into discounted dollars over time they are clearly of practical significance. For example, if we use Equation 2, $30 would lose half of its value in roughly $2\frac{1}{2}$ months, $60 in roughly 5 months, and $85 in roughly 7 months. If discounting rates were independent of amount, these time periods would be equal, regardless of whether the function was hyperbolic or exponential.

It should be noted that we could not estimate parameter values for the 14% of subjects who always chose the delayed reward for one or more of the reward sizes (and thus had very low rates) or the 1% of subjects who always chose the immediate reward for one or more of the reward sizes (and thus had very high rates). Because there are more of the former than the latter, the mean rates we computed probably overestimated the means for the population from which we sampled. Future studies should include additional trials with longer delays to allow parameter estimation for more of those subjects with very low discounting rates.

Because of the inverse relationship between discounting rate and amount, the simple existence of preference reversals does not favor hyperbolic over exponential discounting functions, as discussed in the introduction to this paper. To determine whether hyperbolic or exponential functions better describes human discounting, one needs to compare the two functions quantitatively with delayed reward amount held constant. At present, only two studies have done this.

In one study, using hypothetical rewards, Rachlin et al. (1991) offered subjects choices between $1,000 at varying delays and a number of smaller, immediate rewards. They found that the median delays at which their group of subjects reversed preference for a pair of rewards was reliably better accounted for by a hyperbolic than an exponential function. Because only a single delayed reward size was used, the poorer fit of the exponential function cannot be explained away as due to decreasing discount rates as amount increases.

In a second study, using real rewards, we presented subjects with a series of trials in which the same reward amount was presented at various delays (Kirby & Maraković, 1995). On each trial we estimated the discounted value of the delayed reward by asking subjects to indicate the minimum amount of money that they would accept immediately in exchange for the delayed reward. For each delayed reward, we assessed the relative adequacy of exponential and hyperbolic functions (Equations 1 and 2) by fitting those functions to the discounted values using iterative nonlinear regressions. In every condition and for nearly every subject, the hyperbolic function fit better than the exponential.

Although the weight of the evidence currently favors hyperbolic discounting, the results of the present study indicate that the hyperbolic function in Equation 2 is not adequate (see Green, Fry, & Myerson, 1994, for another shortcoming of this equation). One simple improvement would be to make k an inverse function of amount, $k = j/A$, where the free parameter j is still an individual difference index of impulsiveness, but in different units than k in Equation 2. Substituting this function into Equation 2 yields

$$V = \frac{A}{1 + \left(\frac{j}{A}\right)D}. \tag{3}$$

Applying Equation 3 to the present data, including all delayed reward sizes, yields $j = 0.383$. The overall consistency if we use Equation 3 is

96%, which is reliably higher than that reported above (92%) with Equation 2 [$t(527) = 15.4, p < .0001$]. Thus, Equation 3 does a significantly better job of accounting for subjects' choices across delayed reward sizes than does Equation 1 or 2. Estimating values of j for the small, medium, and large delayed reward sizes yields the values 0.369, 0.377, and 0.365, respectively. None of the pairwise differences among these values are reliably different. Equation 3 better captures the quantitative features of discounting across reward sizes than do previously proposed functions.

The present data also revealed reliable gender differences in discounting. Males discounted more steeply than females, and their discounting rates decreased less sharply with amount than did those of females. Again, although these differences appear to be small, they translate into practically meaningful differences. A $50 reward would lose half of its value in a little over 4 months for males, on average, but it would take a little over 5 months for the same reward to lose half of its value for an average female. This should produce greater impulsiveness in males, which is consistent with the psychometric and personality literature on gender differences in impulsiveness (e.g., Eysenck, Easting, & Pearson, 1984; Salkind & Poggio, 1978).

There is growing evidence that probability discounting and delay discounting are similar in their functional form (Rachlin, 1990; Rachlin et al., 1991). However, because all trials in the present study had an equal probability of being selected by lottery, the introduction of probability itself does not compromise our central conclusion. In fact, the uniform reduction in expected value introduced by the lottery should, if it has any effect, make it more difficult to distinguish changes in discount rate with amount.

Offering subjects a chance of receiving one of their choices, as we did here, is a step in the right direction from using purely hypothetical rewards. However, it remains the case that subjects knew that they were not likely to receive a reward, and further research is needed to show whether the quantitative results found here will generalize to choices between certain rewards. Another step in the right direction would be to pay each subject for one of his or her choices, but this would have been prohibitively expensive with the number of subjects used here. Still, the high consistency in subjects' choices that we observed suggests that subjects were generally very careful in making their choices, even though they were unlikely to obtain a reward. This encourages us to think that the parameter estimation procedure developed here, along with the questionnaire format, could be employed successfully in future research as quick way of estimating people's discounting rates.

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