JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 2002, **77**, 129–146 NUMBER 2 (MARCH)

WITHIN-SUBJECT COMPARISON OF REAL AND HYPOTHETICAL MONEY REWARDS IN DELAY DISCOUNTING

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A within-subject design, using human participants, compared delay discounting functions for real and hypothetical money rewards. Both real and hypothetical rewards were studied across a range that included \$10 to \$250. For 5 of the 6 participants, no systematic difference in discount rate was observed in response to real and hypothetical choices, suggesting that hypothetical rewards may often serve as a valid proxy for real rewards in delay discounting research. By measuring discounting at an unprecedented range of real rewards, this study has also systematically replicated the robust finding in human delay discounting research that discount rates decrease with increasing magnitude of reward. A hyperbolic decay model described the data better than an exponential model.

Key words: delay discounting, real rewards, hypothetical rewards, magnitude, hyperbolic, choice, humans

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Delay discounting implies that the value of a reward declines with increasing delay. This is consistent with the common finding that humans and nonhuman animals often sacrifice a large delayed reward in order to receive a smaller but more immediate reward. Such a choice has been labeled *impulsivity,* whereas the opposite choice has been labeled *self-control* (Ainslie, 1975; Deluty, 1978; Green, Fisher, Perlow, & Sherman, 1981; Logue, 1988; Mischel, Shoda, & Rodriguez, 1989; Rachlin & Green, 1972).

In research with both animals and humans, most delay discounting experiments measure delayed reward value by having participants make a series of choices between an immediately available reward and a delayed reward, while either delay of the larger reward or magnitude of the smaller reward is adjusted. In human studies, the choices are frequently hypothetical (e.g., Green, Fry, & Myerson, 1994; Rachlin, Raineri, & Cross, 1991).

Hypothetical rewards are used instead of real rewards in delay discounting studies for two reasons. First, investigators often study magnitudes of money that they simply cannot afford to pay participants (e.g., \$1,000). Even studying smaller monetary rewards may be cost prohibitive because the determination of a single discounting curve requires several choice presentations. Second, delay discounting research with humans often measures the value of rewards delivered after very long delays such as 20 years or more, making real reward delivery problematic.

One solution for using real rewards is to actually provide participants with the selected option on one or more randomly determined trials throughout the experiment instead of providing the reward for every trial. In addition, delays are limited to experimentally practical durations such as 6 months or 1 year (Kirby, 1997; Kirby & Maraković, 1995, 1996; Kirby, Petry, & Bickel, 1999; Mitchell, 1999; Richards, Zhang, Mitchell, & de Wit, 1999). The intent of using randomly selected real rewards is for the subject to make all choices as though the outcomes were real, because there is a chance that each selected option will be delivered.

Use of hypothetical rewards in most delay discounting experiments with humans calls into question the validity of the results. Real rewards, which are of true interest, may produce results different from those of hypothetical rewards (Kirby, 1997). Comparing delay discounting of real and hypothetical rewards is therefore important for confirming the validity of experiments using hypothetical rewards. Kirby (1997) compared delay discounting of real and hypothetical

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This research was supported by National Institute on Drug Abuse Grants R01 DA 11692 and T32 DA07242. We thank Forest Baker for comments on earlier drafts of this manuscript and Amy Prue for assistance in manuscript preparation.

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rewards across studies. His analysis suggested that real rewards are discounted to a greater extent than hypothetical rewards. However, in addition to methodological differences, studies using real rewards have typically examined much smaller reward magnitudes relative to those examined in hypothetical reward studies, potentially confounding reward type (real or hypothetical) with reward magnitude. To date, no study has compared delay discounting of real and hypothetical rewards within participants.

The present experiment used a within-subject design to measure delay discounting of real and hypothetical rewards. According to Kirby and Maraković (1995), this is a necessary step in the evaluation of hypothetical rewards in delay discounting research with humans. To study real rewards, the probabilistic real reward method described above was utilized. One choice trial from each magnitude was randomly selected, and the option chosen by the participant for that trial was awarded at the specified time (immediately or after a delay). This condition will be referred to as the *real reward* condition. In the *hypothetical reward* condition, participants received none of the selected rewards. Both the real and hypothetical reward conditions measured delay discounting at delays from 1 day to 6 months.

In addition to comparing delay discounting of real and hypothetical rewards, the present experiment employed a range of real reward magnitudes that exceeded those used in previous delay discounting experiments, permitting a systematic test of a well-established finding. Humans discount smaller rewards at a higher rate than larger rewards, a phenomenon known as the magnitude effect (Green et al., 1981; Green, Fry, & Myerson, 1994; Green & Myerson, 1993; Green, Myerson, Lichtman, Rosen, & Fry, 1996; Green, Myerson, & McFadden, 1997; Kirby, 1997; Kirby & Maraković, 1996).

The present experiment also tested another established finding. Normative economic theory holds that rewards are discounted exponentially (e.g., Lancaster, 1963; Meyer, 1976). In contrast, laboratory research with humans and nonhuman animals has supported a hyperbolic decay model (e.g., Ainslie, 1975; Mazur, 1987; Rachlin et al., 1991). Both models were tested for their ability to describe the data in the present study.

METHOD

Participants

Six healthy adult volunteers were recruited though a local newspaper advertisement and posters in the Burlington, Vermont, area. Participants 1, 3, and 6 were female, and the others were male. Mean age was 25 years for both sexes. Volunteers were screened for a history of psychiatric disorder; individuals with a history of psychiatric disorder were not included. Advertisements specified compensation of $15 per hour. Participants also received monetary rewards resulting from choices in the experiment as described below, but the possibility of these additional monetary rewards was not revealed to the participants until the beginning of the research session.

Materials

Each participant was studied in a quiet room with the experimenter for a single research session. A notebook computer running a Microsoft Visual Basic® 6.0 program presented choices to the participant using the choice algorithm described in the Appendix. The participant used a mouse to choose between available options. During the experiment, the screen displayed two large command buttons, one on the left side of the screen and one on the right side, in which the choices were presented. The left button always displayed an immediate reward (e.g., ‘‘$5.00 now’’), and the right button displayed a delayed reward (e.g., ‘‘$10.00 in 1 week’’). A single click of the left mouse button while the cursor arrow was over a command button signaled the selection of that option. Centered on the screen above the two buttons was a circle that was green when the command buttons were available to register a response. After the participant selected an option, the computer presented an audible ‘‘ding’’ sound, and the circle became red for 2 s. When the circle was red, the two choice buttons were nonfunctional; thus, the participant was forced to wait before responding. During this brief waiting time, the command buttons were still visible and displayed the options for the next choice. After 2 s, the circle turned green again, which signaled the opportunity to make the next response. There was no programmed limit to the time the participant could wait before making his or her next response.

Procedure

Instructions and orientation. After signing a consent form, the participant sat in front of the computer and the experimenter read the following instructions aloud.

> For this study, you will be asked to make a series of choices, which will be displayed on this computer screen. There are no right or wrong answers. Please just answer honestly.
>
> For each choice, you will see one box on the left side of the screen, and another box on the right side of the screen. Each box will contain a money amount and also whether that money would be available now or after a delay. For example, you are now being asked to choose between [the immediate reward amount randomly selected by the computer via the procedure described in the Appendix] now, and 50 dollars in 6 months. With the mouse on the table, please point the arrow on the screen over the box with the alternative you prefer. With the arrow on that box, click the left mouse button to choose that alternative. You may now make your first choice.

After the participant made his or her first selection, the experimenter continued.

> As you can see, once you have made your choice, the circle at the top of the screen will turn red momentarily. During this time new alternatives will appear in the boxes, but you will be unable to make your next choice while the circle is red. When the circle is green once again, you are free to make your next choice between the new alternatives.
>
> Please continue making your choices. I will stay here during the initial series of choices only to make sure the procedure is understandable.

The participant continued to make choices until an indifference point was determined between an immediately available smaller amount and $50 delayed by 6 months (procedure described in the Appendix), at which point the computer stopped presenting choices. This series of choices was used to orient the participant to the procedure. The experimenter asked the participant if he or she understood the choice procedure, and all participants indicated that they understood. The experimenter then continued reading the instructions.

> For the rest of the study, some of the choices presented to you will be completely hypothetical. The screen will indicate that the following choices are hypothetical before you are presented with the hypothetical choices. For these questions you will not receive any of the rewards you choose.
>
> However, some of the choices presented to you will be potentially real. The screen will indicate that the following choices are for real money before you are presented with the questions for potentially real rewards. You will be presented choices in which the highest money amount of the two choices will be $10. For other choices, the highest money amount of the two choices will be $25, $100, and $250. For each of these amounts, you will receive one of the choices that you choose. Therefore you will actually receive a total of four rewards that you choose out of all the questions you answer. At the end of the study, you will pick a number out of a bag for each amount category. The number you randomly pick for each category will correspond to the question number for that category.
>
> For example, at the end of the study, you will first pick a number for the $10 category out of the bag. Let us suppose that you pick the number 50. We would then look at the list of all real choices you made for the $10 category on the computer. Together, we will look to the 50th question to determine what your reward will be and when you will receive it. Suppose in our example that the 50th question asked you to choose between $5 now and $10 in 1 week, and you chose $10 in 1 week. I would then give you the option of having a $10 check mailed to an address you specify in 1 week, or having you come back to this building and pick up a check for $10 in 1 week. If you had chosen to have $5 now, that amount would be included in the check given to you before you leave here today. This process will also be repeated for the $25, $100, and $250 categories.
>
> Therefore, for the series of real choices, every choice has a chance of being one of the real choices for which you will actually receive the reward. Given this fact, you should make every choice in the real series as though it were the one that will actually be rewarded, because there is a chance that it is the choice to be awarded.
>
> Although you will not receive any of the choices you make in the hypothetical series of questions, I would like you to make these choices as though they are real. There are no right or wrong answers, so please just answer honestly on all questions.
>
> During the study you will be given two 5-

minute breaks. The computer will indicate when these periods begin and you will be unable to continue until 5 minutes have elapsed.

I want you to fully understand the procedure, so please ask any questions you might have now. We can go though the computer orientation or these instructions again if you desire. It is essential that you understand the procedure before we move on.

Some participants asked if the questions for potentially real rewards would be distinguished from the hypothetical questions. The experimenter restated that the computer screen would specify whether the questions would be for the real or hypothetical reward condition before each series. Some participants also asked the experimenter to review the methods by which the real rewards would be selected, and the experimenter explained this procedure again. No participant asked to experience the orientation again when asked. The experimenter then left the participant alone in the room, closed the door, and waited outside the room. Two 5-min breaks were given in which the participant was free to leave the experimental room. These two breaks divided the session into three approximately equal time segments. The total session length was approximately 2.5 hr.

Experimental design. Participants were exposed to two conditions, one in which all choice questions were hypothetical and one in which all questions were potentially for real money consequences. Participants 3 and 4 were exposed to the real reward condition first and the hypothetical reward condition second, and the other participants received the opposite order. Within the series of potentially real choices, four reward magnitudes were examined: \$10, \$25, \$100, and \$250. Indifference points were determined at each of these magnitudes at five different delays: 1 day, 1 week, 2 weeks, 1 month, and 6 months. The hypothetical series examined the magnitudes and delays stated above, along with the additional magnitudes of \$1,000 and \$2,500 and the additional delays of 1 year, 5 years, and 25 years. The computer varied the smaller, immediately available amount across trials according to the algorithm described in the Appendix. However, the larger delayed amount stayed the same until an indifference point was determined. After an indifference point was determined, the delay for the larger reward increased to the next duration. When all indifference points for a magnitude at each delay were found, the magnitude was changed and the delay returned to the first delay (1 day) again. Participants 1, 3, and 5 received an ascending order of reward magnitudes. The other participants received a descending order of reward magnitudes. Choice presentations ended once indifference points had been determined for each magnitude at each delay.

Upon completion of all choice trials, one choice presented during the real series was randomly selected for each magnitude as described in the instructions. Participants then received money for their time and for any randomly selected trials in which the chosen reward was immediately available.

Data analysis. Nonlinear regression was used to fit both the hyperbolic decay model, expressed in Equation 1, and the exponential model, expressed in Equation 2, to the obtained indifference points.

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

$$V_p = Ve^{-kD}. \tag{2}$$

In both equations, V_p is the present (discounted) value of the reward, V is the objective (undiscounted) value of the reward, D is the delay from the choice until the receipt of the reward, and k is a free parameter. In Equation 2, e is Euler's number. Using only delays up to 6 months (which was the longest delay used for real rewards), parameter estimates for both Equations 1 and 2 were determined for each reward magnitude, for both real and hypothetical reward conditions. Hypothetical reward parameters for Equation 1 were also determined by using all delays up to 25 years. The time unit of days was used for the D variable in all regression analyses; therefore, all k estimates carry the reciprocal of days (i.e., days^{-1}) as units.

Discounting equation parameter estimation typically results in skewed distributions (Myerson & Green, 1995; Rachlin et al., 1991; Richards et al., 1999). That is, if discounting is shallow over the time range studied, indifference points will asymptotically approach zero. Therefore, analyses must either normalize the distribution through transformation of the data or utilize nonparametric statistics. A logarithm (Base 10) transformation was used to normalize the distributions of parameter estimates. A Pearson's correlation examined the strength of the relation between log-transformed real and hypothetical reward parameter estimates, calculated with delays up to 6 months, for the 24 conditions for which both real and hypothetical reward parameters were examined (four magnitudes each for 6 participants). Also using log-transformed parameter estimates, a Pearson's correlation examined the strength of the relation between hypothetical reward parameters estimated with delays limited to 6 months and hypothetical reward parameters estimated with the full range of delays extending to 25 years. Comparisons of R^2 goodness-of-fit values between Equation 1 and Equation 2 parameter estimates, calculated with delays up to 6 months, were performed using Wilcoxon matched-pairs signed-ranks tests because goodness-of-fit value distributions were skewed.

RESULTS

Figures 1 through 4 show indifference points and the best fits of Equation 1, calculated with delays up to 6 months, for both real and hypothetical rewards for each participant. The \$10, \$25, \$100, and \$250 magnitudes are shown in Figures 1, 2, 3, and 4, respectively. Figure 1 reveals that Participants 1, 2, 4, and 5 discounted \$10 hypothetical rewards more steeply than \$10 real rewards. For Participants 3 and 6, however, discounting curves are steeper for the real rewards than for the hypothetical rewards. Figure 2 reveals steeper discount curves for \$25 hypothetical rewards for Participants 2, 3, and 5 and steeper \$25 real reward discounting functions for Participants 1, 4 and 6. Figure 3 reveals steeper discounting functions for the \$100 hypothetical rewards for Participants 2, 4, and 6, steeper discounting functions for the \$100 real rewards for Participant 5, and a similar discounting rate for real and hypothetical rewards for Participants 1 and 3. Figure 4 reveals that the \$250 discounting functions are steeper for hypothetical rewards for Participants 1, 2, 3, and 6, whereas real reward functions are steeper for Participants 4 and 5. These results suggest that within each of the magnitudes examined, there was no systematic difference in discounting between real and hypothetical rewards for 5 of the 6 participants. Neither the order of real and hypothetical presentations, the order of magnitude presentation, nor participant gender showed a systematic effect on results.

Figure 5 shows hyperbolic k parameter estimates as a function of magnitude for each participant individually and for median k values across participants. Parameters have been estimated with delays limited to 6 months in both the real reward and hypothetical reward conditions and all magnitudes. This graph suggests that Participants 1, 3, 4, 5, and 6 exhibited no systematic differential discounting for the two reward types. However, Participant 2 consistently discounted hypothetical rewards to a greater extent than real rewards, as revealed by higher k values at all magnitudes. This pattern for Participant 2 is also revealed by inspection of this participant's indifference points and discounting functions throughout Figures 1 through 4. Figure 5 also reveals systematic differences in discounting across participants. Participants 5 and 6 had relatively high discount rates, and Participants 1, 3, and 4 had lower discount rates. These differences were relatively consistent across magnitudes, and are apparent when either the real rewards or hypothetical rewards are considered independently. Real reward discount rates for Participant 2 were moderate compared to other participants' hypothetical or real reward discount rates. However, hypothetical reward discount rates for Participant 2 were higher at all reward magnitudes than any other participant's real or hypothetical reward discount rates, with the exception of the \$10 hypothetical reward of Participant 5.

The magnitude effect was revealed in Figure 5 for Participants 1, 2, 3, and 5. For these 4 participants, discounting rate decreased with increasing reward magnitude. In other words, the smaller rewards were discounted more steeply than the larger rewards. Although there was some variability in this effect for individual participants, a general trend is evident. When comparing the discounting of the smallest and largest rewards (i.e., \$10 and \$250), the \$10 magnitude had a higher discount rate than the \$250 magnitude for all participants in both the real and hypothetical reward conditions.

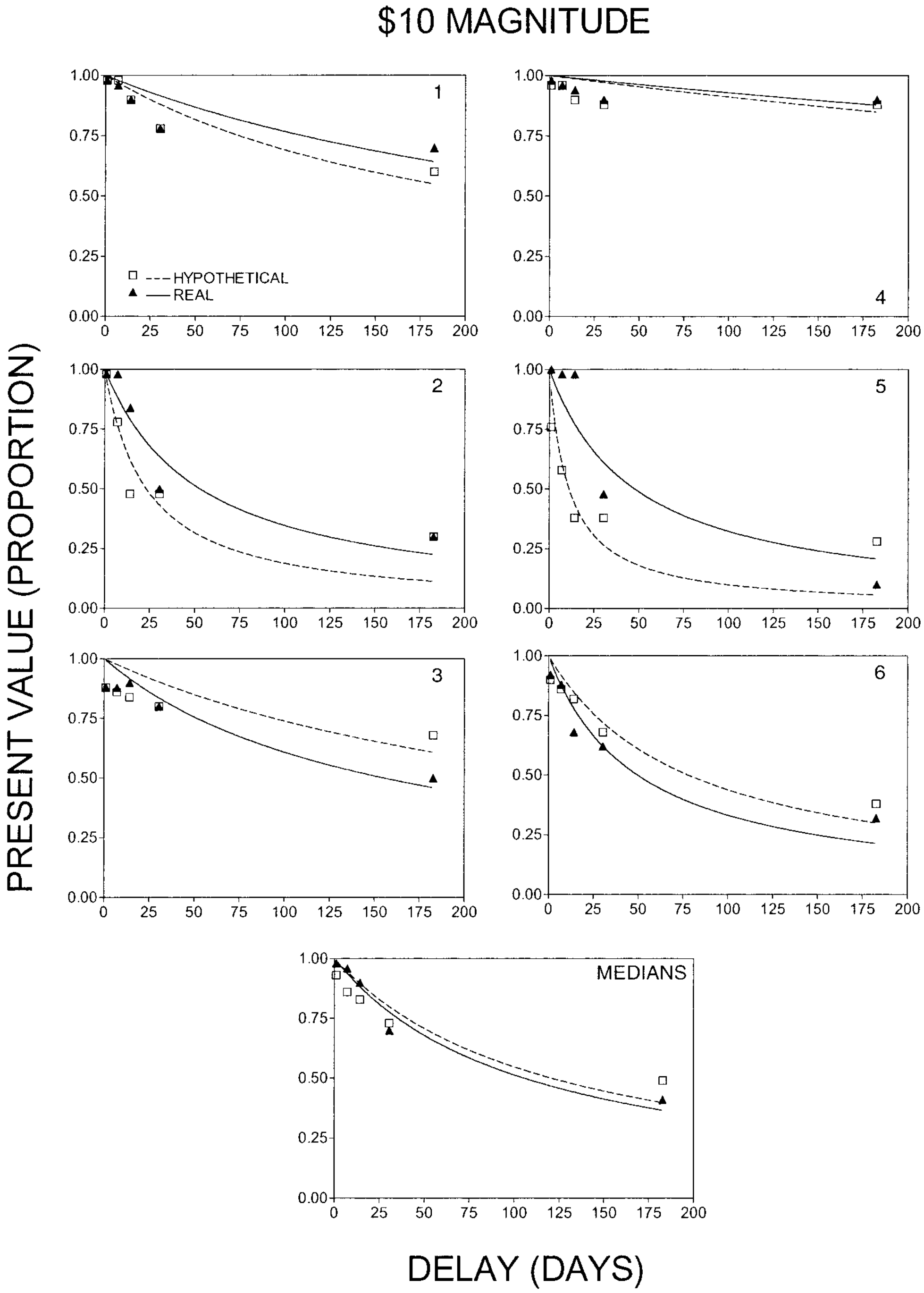

Fig. 1. Hyperbolic (Equation 1) discounting functions for $10 fit to the real reward and hypothetical reward indifference points for each participant and the median indifference points.

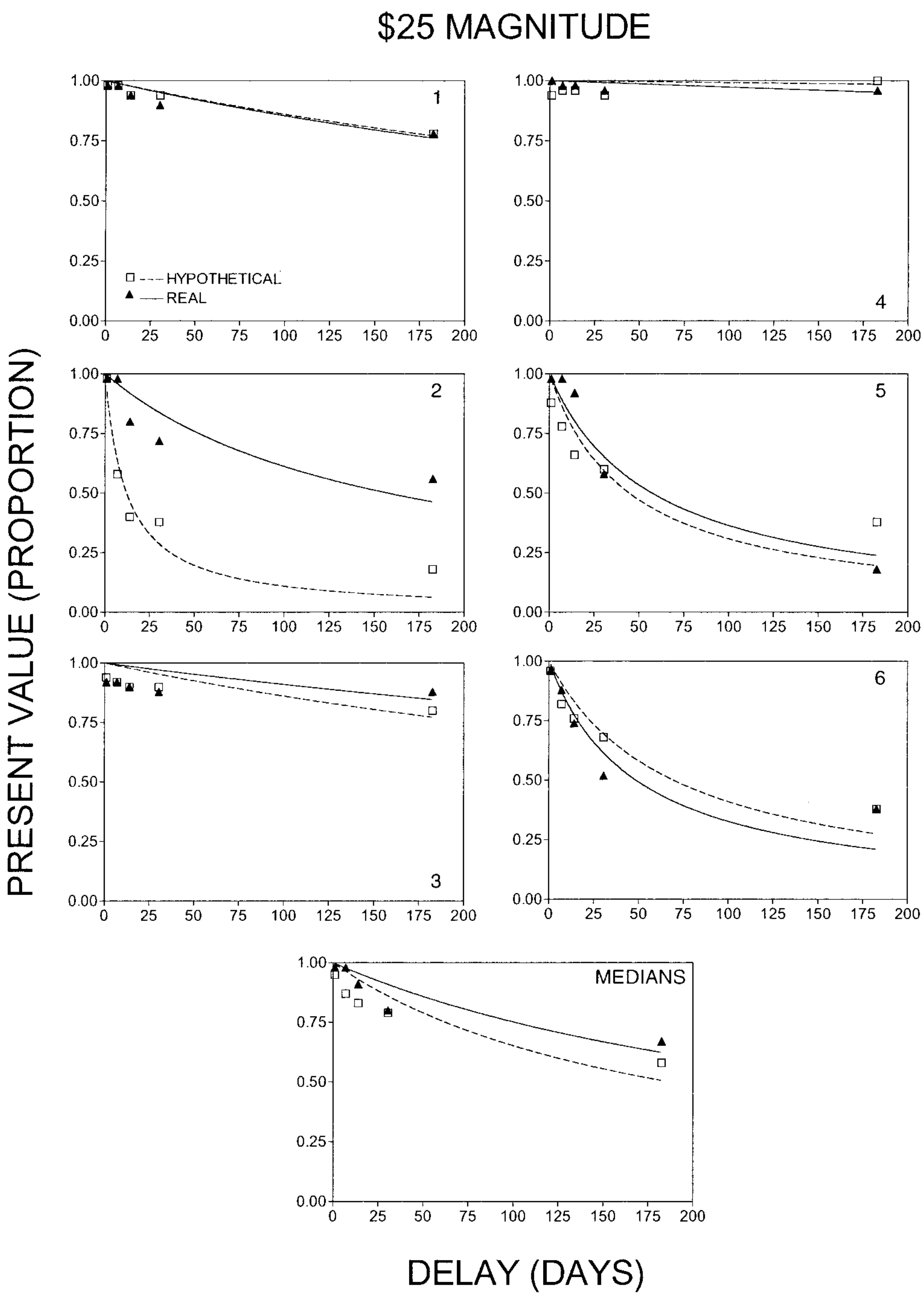

Fig. 2. Hyperbolic (Equation 1) discounting functions for $25 fit to the real reward and hypothetical reward indifference points for each participant and the median indifference points.

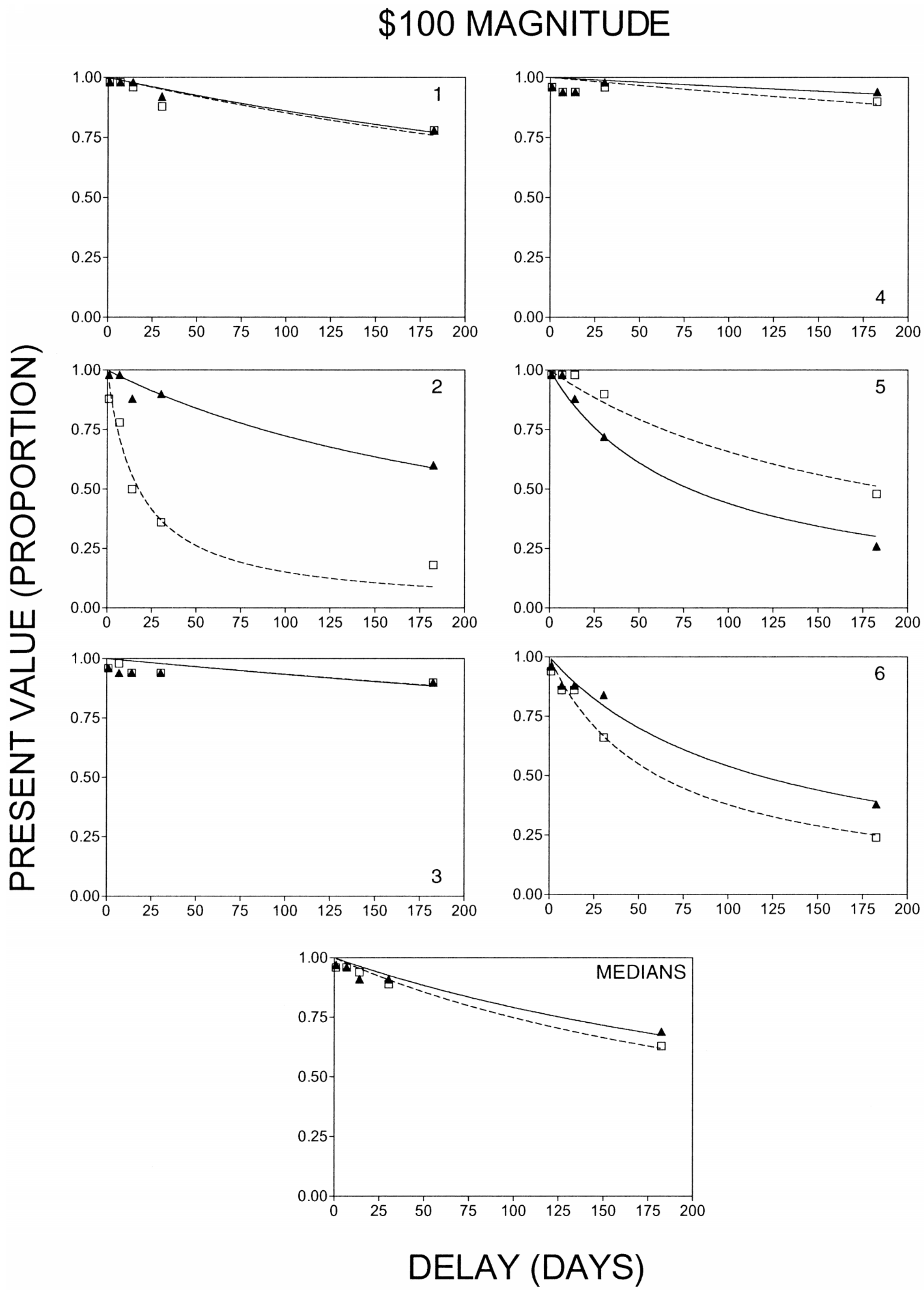

Fig. 3. Hyperbolic (Equation 1) discounting functions for $100 fit to the real reward and hypothetical reward indifference points for each participant and the median indifference points.

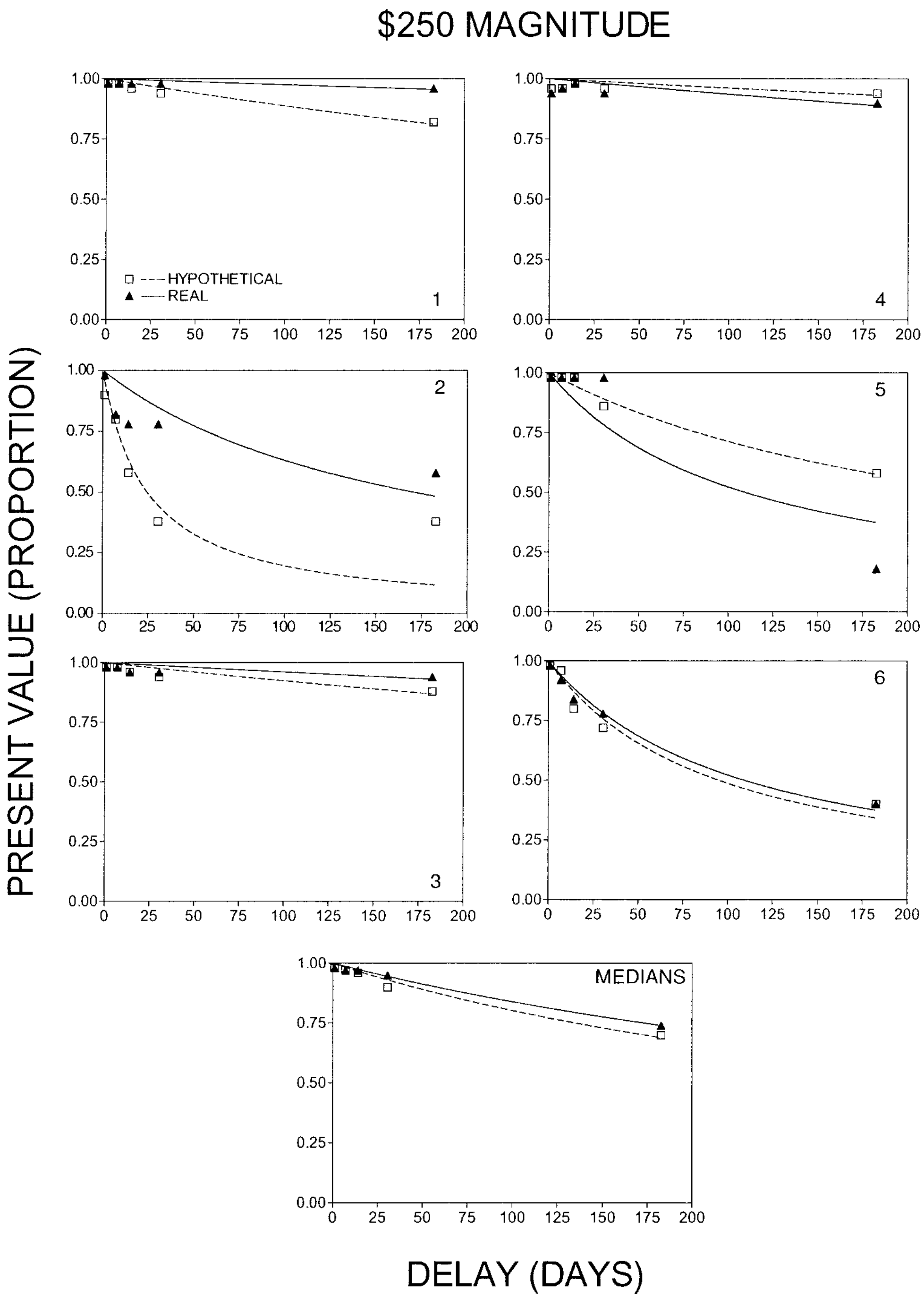

Fig. 4. Hyperbolic (Equation 1) discounting functions for $250 fit to the real reward and hypothetical reward indifference points for each participant and the median indifference points.

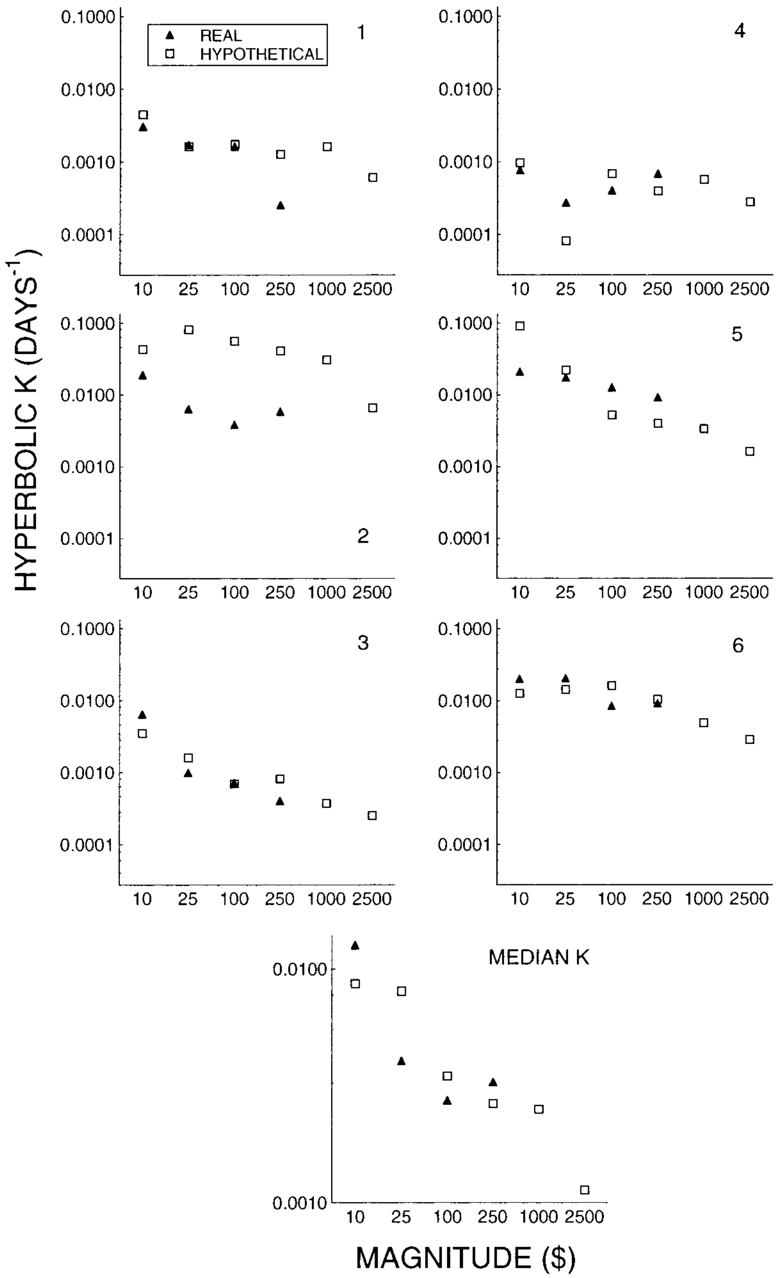

Fig. 5. Hyperbolic k parameter in day^{-1} units plotted as a function of magnitude for each participant and for the median k values. All y axes are in logarithmic scale. Note the different y-axis scale on the graph of the medians.

Figure 6 demonstrates a positive correlation between log-transformed values of real reward hyperbolic k values and log-transformed hypothetical reward hyperbolic k values (Pearson's $r = .831$, $p < .001$). This correlation reveals that the variability associated with reward type (i.e., real or hypothetical) is relatively small compared to other sources of variability such as individual participant differences and magnitude. Figure 7 demonstrates a positive correlation between log-transformed hypothetical reward parameters estimated with delays limited to 6 months and log-transformed hypothetical reward param-

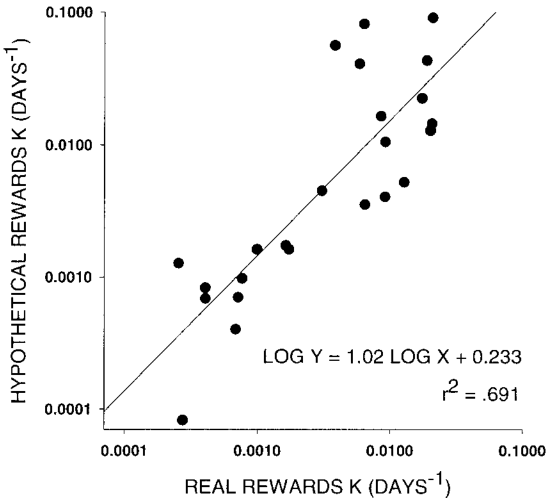

Fig. 6. Least squares linear regression of log-transformed hyperbolic *k* estimates of the real reward and the hypothetical reward conditions. Untransformed data are presented on double logarithmic axes.

eters estimated with the full range of delays extending to 25 years (Pearson's $r = .918$, $p < .001$).

Table 1 displays *k* parameter estimates and R^2 goodness-of-fit estimates for both Equation 1 and Equation 2 when using only delays

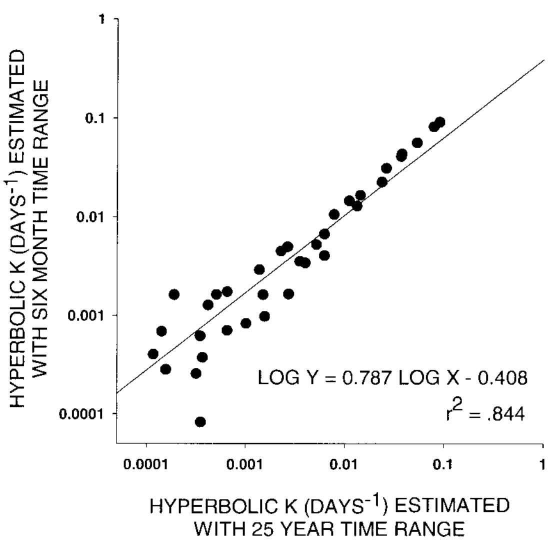

Fig. 7. Least squares linear regression of the log-transformed hypothetical reward parameters estimated with delays limited to 6 months and log-transformed hypothetical reward parameters estimated with the full range of delays extending to 25 years. Untransformed data are presented on double logarithmic axes.

up to 6 months. For some series of indifference points, nonlinear regression was unable to account for more variance than did the mean, which is denoted by an R^2 equal to zero. This was true for all *k* values for Participant 4 and most series for Participant 3. In cases in which nonlinear regression was unable to account for more variance than the mean, essentially no discounting occurred for the 6-month range used to calculate these values. In other words, preference for the larger, later reward was not deterred by the addition of up to 6 months of delay; thus, the discounting function resembles a horizontal line at the top of the graph (i.e., near a present value proportion equal to one). When Equation 1 parameter estimates were calculated using all delays (up to 25 years), the median R^2 for the hypothetical reward condition was .916, and in only one case of 36 (Participant 4, $1,000 magnitude) did this equation account for less variance than did the mean (i.e., $R^2 = 0$). These fits were substantially better than Equation 1 fits using delays limited to 6 months (median reported below). The higher R^2 values resulting from the additional delays suggest that the narrow time window of 6 months was responsible for many of the relatively poor fits reported in Table 1.

Using only delays up to 6 months, the median value of R^2 for the real rewards was .817 for Equation 1, compared to an R^2 of .609 for Equation 2. A Wilcoxon matched-pairs signed-ranks test revealed that Equation 1 accounted for significantly more variance than Equation 2 in the real reward condition ($T = 20$, $n = 24$, $p < .05$). Participant 5 was the only exception to this trend. At all four magnitudes, the exponential equation accounted for more variance than the hyperbolic equation for this participant. Using only delays up to 6 months, the median value of R^2 for hypothetical rewards was .802 for Equation 1 and .611 for Equation 2. A Wilcoxon matched-pairs signed-ranks test also showed Equation 1 to account for more variance than Equation 2 in the hypothetical reward condition ($T = 4$, $n = 24$, $p < .001$). The only exception to this trend was the $100 magnitude for Participant 5, for which Equation 2 accounted for more variance than the hyperbolic equation did.

Table 1

Estimated k values (days^{-1}) for real and hypothetical rewards fit to both the hyperbolic and exponential equations.

		Hyperbolic				Exponential			
		Real		Hypothetical		Real		Hypothetical	
Participant	Magnitude ($)	k	R^2	k	R^2	k	R^2	k	R^2
1	10	0.0031	.556	0.0045	.860	0.0023	.471	0.0031	.793
	25	0.0017	.832	0.0016	.924	0.0015	.803	0.0014	.911
	100	0.0016	.948	0.0017	.801	0.0014	.936	0.0015	.771
	250	0.0003	.000[a]	0.0013	.912	0.0002	.000[a]	0.0011	.899
2	10	0.0189	.905	0.0432	.802	0.0119	.795	0.0329	.579
	25	0.0063	.704	0.0815	.909	0.0039	.572	0.0520	.769
	100	0.0038	.947	0.0563	.940	0.0029	.928	0.0395	.856
	250	0.0059	.325	0.0410	.647	0.0037	.129	0.0338	.340
3	10	0.0064	.804	0.0035	.000[a]	0.0043	.723	0.0026	.000[a]
	25	0.0010	.000[a]	0.0016	.000[a]	0.0009	.000[a]	0.0014	.000[a]
	100	0.0007	.000[a]	0.0007	.000[a]	0.0007	.000[a]	0.0007	.000[a]
	250	0.0004	.000[a]	0.0008	.598	0.0004	.000[a]	0.0008	.575
4	10	0.0008	.000[a]	0.0010	.000[a]	0.0007	.000[a]	0.0009	.000[a]
	25	0.0003	.000[a]	0.0001	.000[a]	0.0003	.000[a]	0.0001	.000[a]
	100	0.0004	.000[a]	0.0007	.000[a]	0.0004	.000[a]	0.0006	.000[a]
	250	0.0007	.000[a]	0.0004	.000[a]	0.0006	.000[a]	0.0004	.000[a]
5	10	0.0209	.873	0.0908	.380	0.0152	.908	0.0563	.000[a]
	25	0.0175	.938	0.0224	.581	0.0117	.945	0.0106	.000[a]
	100	0.0128	.982	0.0052	.973	0.0081	.983	0.0039	.991
	250	0.0092	.829	0.0040	.98	0.0069	.911	0.0031	.971
6	10	0.0202	.892	0.0128	.889	0.0110	.645	0.0069	.713
	25	0.0206	.833	0.0144	.867	0.0108	.512	0.0073	.643
	100	0.0085	.965	0.0165	.983	0.0056	.953	0.0101	.938
	250	0.0092	.984	0.0105	.951	0.0057	.929	0.0061	.857

[a] R^2 of .000 indicates that the equation provided a poorer fit than did the mean.

DISCUSSION

The experiment produced three important findings. First, the results suggest that, with the exception of 1 participant, there was no systematic difference between the rate of discounting of real rewards and hypothetical rewards. In addition, this study replicated two previous findings and extended these findings to previously unexamined real reward magnitudes: (a) Smaller magnitude rewards were discounted at a higher rate than larger magnitude rewards, and (b) the hyperbolic decay model expressed in Equation 1 achieved better fits than the exponential model expressed in Equation 2.

The present study failed to demonstrate systematic differences in discounting rate for real and hypothetical delayed rewards for most participants. Research on delay discounting in humans has relied heavily on the use of hypothetical choice procedures. In fact, hypothetical reward techniques have provided much support for such phenomena as the hyperbolic model of discounting (e.g., Rachlin et al., 1991), the magnitude effect (e.g., Green et al., 1997), the greater discounting of rewards relative to losses (e.g., Thaler, 1981), and preference reversals over time (e.g., Green, Fristoe, & Myerson, 1994). Validation of choice procedures using hypothetical rewards thus provides additional support for these findings.

Kirby (1997) compared previous studies that had used real rewards with those that had used hypothetical rewards. Discounting was greater in the real reward experiments than in the hypothetical reward experiments. In addition, discounting decreased more sharply with increasing magnitude in real reward experiments than it did in the hypothetical reward experiments. Kirby (1997) presented two possible explanations for these results. One is that, all else being equal, real rewards are discounted more steeply than hypothetical rewards, and the magnitude effect (the inverse relation between discount rate and magnitude) is more pronounced in real rewards than in hypothetical rewards.

The other explanation proposed by Kirby (1997), which is consistent with the present results, is that these apparent differences between real and hypothetical reward studies are actually an effect of the different magnitudes typically used in the two methods. Real rewards have been studied at smaller reward magnitudes because of financial limitations. Therefore, those studies that have examined real rewards may obtain higher discounting rates because smaller magnitudes are discounted more than larger magnitudes (i.e., the magnitude effect). In addition, the fact that discounting decreased more sharply with increasing magnitude in real reward experiments can also be explained by the magnitude difference between real and hypothetical reward studies because discounting rates decrease in a negatively decelerating fashion with respect to magnitude (Green et al., 1997). That is, the magnitude effect itself gets weaker with increasing magnitude.

Figure 8 plots k estimates according to Equation 1 for both real and hypothetical reward studies that have examined the discounting of at least two reward magnitudes. The studies represented here used various methods. The k parameters plotted in Figure 8 are either taken from reported k parameters in original publications if Equation 1 was used, calculated from reported indifference points in original publications, extrapolated from figures in published articles, or extrapolated from two similar figures shown by Kirby (1997). The displayed k values represent various measures of central tendency of k in these studies, depending on those reported in the original publications. Figure 8 presents all k parameters in per-day units (some studies report k parameters that have been calculated using different units of time and so have been linearly transformed here). Figure 8 suggests that real rewards have indeed been discounted more steeply as a function of their lower magnitude. In addition, it appears that the slope is not related to whether the reward is real or hypothetical as much as it is related to magnitude.

The similarity of real reward and hypothetical reward discounting functions may encourage investigators to use hypothetical rewards in lieu of real rewards in future delay discounting measurement when financial constraints preclude the costs of giving real rewards. This may be particularly important if delay discounting is to be used in clinical settings, a role that may be appropriate considering recent studies such as those reporting high discount rates among drug dependents (for review, see Bickel & Marsch, 2001) and some groups of psychiatric patients (Crean, de Wit, & Richards, 2000). The validity of procedures using hypothetical rewards in delay discounting measurement would allow economical application in clinical assessment. The strong relation between log-transformed hypothetical reward parameters estimated with delays limited to 6 months and log-transformed hypothetical reward parameters estimated with the full range of delays extending to 25 years suggests that clinical applications may be kept relatively brief without sacrificing validity. However, the 1 participant who demonstrated a systematic trend to discount hypothetical rewards more than real rewards suggests that a degree of caution be used when interpreting results from methods using hypothetical rewards. Results obtained by using hypothetical rewards might not be indicative of real reward discounting in all individual participants.

This study described delay discounting across a relatively wide range of magnitudes in both real and hypothetical reward conditions. This range includes previously unexamined magnitudes of real rewards. For both real and hypothetical rewards, a magnitude effect was found; that is, the discounting rate decreased as magnitude of reward increased. This pattern is consistent with previous findings in humans (Green et al., 1981, 1996, 1997; Green, Fry, & Myerson, 1994; Green & Myerson, 1993; Kirby, 1997; Kirby & Maraković, 1996).

Consistent with previous research (e.g., Rachlin et al., 1991), this study also demonstrated that the hyperbolic equation accounts for more variance in the indifference-point data than the exponential equation does. The present study extended these findings to a range of real rewards that remained unexamined to date, adding to the growing evidence of generality in this finding.

In conclusion, the data presented here suggest that choices made in response to hypothetical rewards may act as a valid proxy for

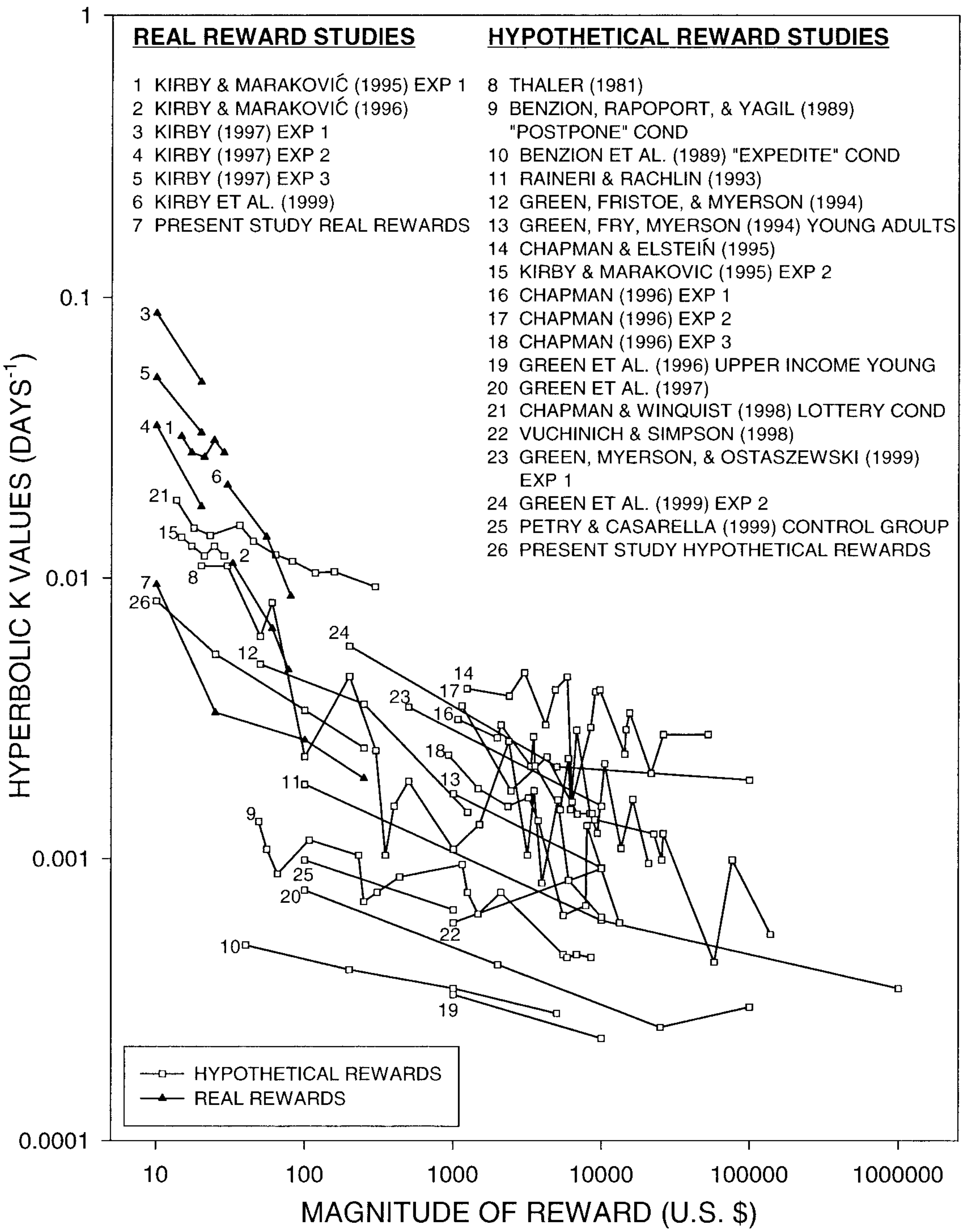

Fig. 8. Studies that have measured delay discounting at different magnitudes. Hyperbolic k values in day^{-1} units are plotted against magnitude of rewards in U.S. dollars on double logarithmic axes. Data points for a particular study are connected with lines. A number is displayed near the smallest magnitude data point for the corresponding study in the legend.

real reward choices in delay discounting research. This supports the validity of various phenomena that have been unveiled by delay discounting assessment because the empirical studies in this literature have to a great extent depended on hypothetical choice methods. The present findings justify the cautious use of hypothetical rewards in delay discounting research, particularly in answering research or clinical questions that might otherwise remain unanswered if the only option were real rewards.

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Received January 23, 2001
Final acceptance November 8, 2001

APPENDIX

Choice algorithm. All trials consisted of a choice between two monetary rewards: one smaller, more immediate reward and one larger delayed reward. The computer set the larger delayed reward equal to the dollar magnitude for which the discounting rate was being determined. For example, when determining the discounting rate for $10, the computer set the larger delayed reward option to $10 at some delay for all trials. The computer varied the magnitude of the smaller, more immediate reward according to a double limit procedure adapted from the one reported by Richards et al. (1999). This procedure is diagrammed in Figure 9.

The computer held values for four limits, two outer limits and two inner. The two outer limits (the outer upper limit and the outer lower limit) bound an area that represented the program's ''best guess'' for the location of the indifference point. These two limits adjusted and eventually converged on an indifference point. However, to protect against any single answer directly controlling the movement of these outer limits (and thus potentially converging on an unconfirmed indifference point), the two inner limits (the values of which remained within the outer limit bound region) served to buffer the effect of individual choice selection on the outer limits. Specifically, a single choice selection immediately changed the inner limit bound range, but only changed the outer limits if the choice confirmed or disconfirmed the best guess represented by the inner limit bound range.

Limit values for the first trial of each indifference-point determination were as follows. The two upper limits were set to the value of the larger delayed reward, and the two lower limits were set to a value of zero. Throughout all trials, the outer upper limit was either greater than or equal to the inner upper limit, and the outer lower limit was either less than or equal to the inner lower limit. The magnitude of the smaller, more immediate reward was a multiple of 2% of the larger delayed reward magnitude and was randomly picked from within the inclusive range of the upper and lower outer limits.

After each choice selection by a participant, the computer adjusted one or more of the four limits, and the next choice was randomly picked again from within the inclusive range of the outer limits, the values of which were potentially different from those in the preceding iteration. The method used to adjust the limits depended upon two factors: whether the smaller, more immediate reward or the larger delayed reward was chosen, and the magnitude of the current smaller, more immediate reward in relation to the two inner limits. To provide examples for each of the following cases, each scenario will be illustrated as if a $10 indifference point were being determined, the current outer upper limit were $9, the current inner upper limit were $7, the current inner lower limit were $3, and the current outer lower limit were $1.

If the participant chose the smaller, more immediate reward, three possible scenarios followed. If the smaller, more immediate reward magnitude was less than the inner upper limit, then the outer upper limit took the value of the inner upper limit, and the upper inner limit took the value of the current smaller, more immediate reward. As an example using the hypothetical limits above, if the smaller, more immediate reward were $5 and were chosen, the outer upper limit would change from $9 to $7, and the inner upper limit would change from $7 to $5. If the smaller, more immediate reward magnitude chosen had been greater than or equal to the inner upper limit, then the outer upper limit was assigned the value of the current smaller, more immediate reward. For example, if the smaller, more immediate reward had been $8 and the participant had chosen it, then the outer upper limit would change from $9 to $8, and the inner limit would remain $7. If the smaller, more immediate reward magnitude was less than the inner lower limit, then the outer lower limit was set to zero, and the inner lower limit was assigned the value of the current smaller, more immediate reward.

Therefore, if the smaller, more immediate reward were $2, and this was chosen over the larger delayed reward, the outer lower limit would decrease from $1 to $0, and the inner lower limit would decrease from $3 to $2. Of course, if the smaller, more immediate reward were less than the inner lower limit, it would also be less than the inner upper limit and therefore the adjustments to the two upper limits would occur simultaneously with

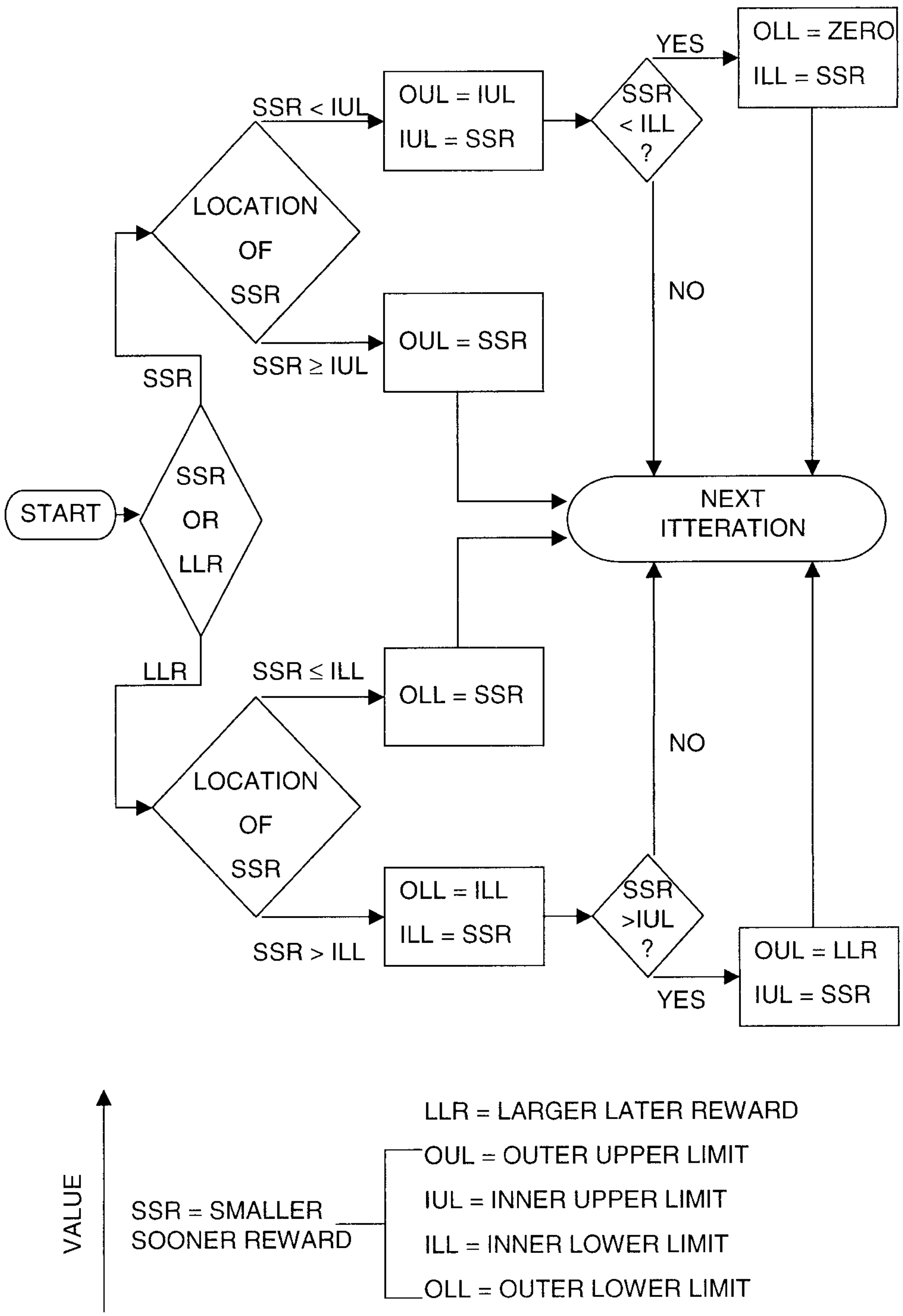

Fig. 9. Choice algorithm used to locate indifference points. Rectangles represent a process in which the variable on the left side of the equation takes the value of the variable on the right side. Diamonds indicate differential outcomes depending on the condition inside the diamond. The procedure is repeated until the difference in value between the OUL and the OLL is 2% or less of the value of the larger delayed reward.

the changes to the two lower limits. Any limits not mentioned for each circumstance above retained their value into the next iteration. These contingencies tended to lower the value of the smaller, more immediate reward if it had been selected, bringing the participant closer to indifference between the smaller, more immediate reward and the larger delayed reward.

Selection of the larger delayed reward resulted in one of the following changes. If the smaller, more immediate reward magnitude was greater than the inner lower limit, then the outer lower limit was assigned the value of the inner lower limit, and the inner lower limit took the value of the smaller, more immediate reward. Again using the hypothetical limits given above, if the smaller, more immediate reward had been $5 and the larger delayed reward was chosen, then the outer lower limit would increase from $1 to $3, and the inner lower limit would increase from $3 to $5. If the smaller, more immediate reward was less than or equal to the inner lower limit, then the outer lower limit took the value of the smaller, more immediate reward. For example, if the smaller, more immediate reward had been $2 and the larger delayed reward was chosen, then the outer lower limit would have changed from $1 to $2, and the inner lower limit would have remained $3. Finally, if the smaller, more immediate reward was greater than the inner upper limit, then the outer upper limit was assigned the value of the larger delayed reward and the inner upper limit was assigned the value of the smaller, more immediate reward.

Therefore if the smaller, more immediate reward had been $8 and the larger delayed reward was chosen, then the outer upper limit would have risen from $9 to $10, and the inner upper limit would have risen from $7 to $8. If the smaller, more immediate reward were greater than the inner upper limit, it was also greater than the inner lower limit and therefore the changes to the two lower limits stated above were implemented simultaneously with these changes to the two upper limits. Again, any limits not mentioned within any of these three particular circumstances remained unchanged. In short, these contingencies tended to increase the value of the smaller, more immediate reward had the larger delayed reward been chosen, thus bringing the participant closer to a point of indifference between the smaller, more immediate reward and the larger delayed reward.

For each indifference-point determination, both the inner and outer upper limits started with a value equal to the larger delayed reward, and both the inner and outer lower limits were set at zero. The smaller, more immediate reward was randomly determined as described above, and the participant's response adjusted the limits as described above. The upper and lower outer limits gradually converged if the participant made consistent responses, and if a response by the participant reset the limit such that the difference between the upper and lower outer limits was equal to 2% or less of the larger delayed reward magnitude, then the value of the current smaller, more immediate reward was deemed the indifference point for the larger delayed reward magnitude discounted at that delay, and the procedure moved on to determine the next indifference point in the sequence.