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Humans' Temporal and Probabilistic Discounting Derived from Choice Proportions in a Choice Situation

SAEKI Daisuke and Masato ITO

Few studies have examined humans' temporal and probabilistic discounting in choice situations where participants experience delays and probabilities by choosing alternatives repeatedly. The present study measured temporal and probabilistic discounting for six adult humans using concurrent-chains schedules: Variable-interval schedules were arranged in the initial links, delays and probabilities of reinforcement were varied in the terminal links, and consummatory responses were required to receive points as reinforcers later exchangeable for money. Each participant was exposed to four different pairs of delays (from 2 s vs. 2 s to 2 s vs. 40 s) and probabilities (from 1.0 vs. 1.0 to 1.0 vs. .65). As a result, temporal and probabilistic discounting were well described by the matching law incorporating an exponential function as well as a hyperbolic function. Further, there was a positive correlation between temporal and probabilistic discounting rates. These findings suggest that the temporal and probabilistic discounting are the same process.

Key words: choice, temporal and probabilistic discounting, concurrent-chains schedule, screen touch, humans.

Discounting of future rewards or uncertain rewards in humans have been studied with hypothetical rewards presented on cards or in questionnaires, or in a situation in which only one of the chosen rewards were realized (e.g., Benzion, Rapoport, & Yagil, 1989; Green, Fry, & Myerson, 1994; Green, McFadden, & Myerson, 1997; see Green & Myerson, 2004 for a review; Kirby, 1997; Kirby & Maraković, 1995, 1996; Lane, Cherek, Pietras, & Tcheremissine, 2003; Rachlin, Raineri, & Cross, 1991; Richards, Zhang, Mitchell, & de Wit, 1999). For example, Rachlin et al. (1991) presented human participants with a series of choice trials between two hypothetical rewards each of which was represented by a card. One of the rewards was a delayed or probabilistic $1,000, and the other was a certain reward of variable amount available immediately. For various delays or probabilities, each participant was required to indicate his or her preference by pointing to one of the cards. From these choices, the values of the certain-immediate reward subjectively equivalent to the delayed $1,000 or the probabilistic $1,000 (i.e., indifference points) were obtained. From these indifference points, Rachlin et al. found that subjective values of the delayed reward were better described by a hyperbolic function (Mazur, 1987) rather than by an exponential function. The hyperbolic function is given by the following equation:

$$v = \frac{A}{1+kD}, \tag{1}$$

where v is the discounted value of a delayed reward of amount A, D is the delay to its receipt, and k is an empirical constant proportional to degree of temporal discounting. The exponential function is given by the following equation:

$$v = Ae^{-kD}. \tag{2}$$

Further, Rachlin et al. (1991) tested the applicability of a hyperbolic and exponential function to the discounting of probabilistic rewards. Again, they found that the discounting of probabilistic rewards was better described by a hyperbolic function than by an exponential function. The hyperbolic function for the probabilistic discounting is given by the following form:

$$v = \frac{A}{1+h\Theta}, \tag{3}$$

where Θ represents the odds against receipt of a probabilistic reward, and h is an empirical constant proportional to degree of probabilistic discounting. It is defined that $\Theta = (1/p) - 1$, where p is the probability of receipt of a reward. Thus, odds against is represented by the average number of losses expected before a win in repeated gambles. As in the case of temporal discounting, the exponential function for the probabilistic discounting is given by the following equation:

$$v = Ae^{-h\Theta}. \tag{4}$$

Studies on human discounting have consistently found that both temporal and probabilistic discounting are better described by a hyperbolic function rather than by an exponential function (e.g., Green et al., 1997; Kirby, 1997; Kirby & Maraković, 1995; Myerson & Green, 1995; Rachlin et al., 1991; Richards et al., 1999). In these studies, one of two types of procedures has been typically used for measuring indifference points: In one procedure, hypothetical rewards are presented on cards (Rachlin et al., 1991), in questionnaires (Benzion et al., 1989), or on a computer monitor (Green, Ostaszewski, & Myerson, 1999), whereas, in the other procedure, one reward that is randomly selected in a series of choices in an experiment (Richards et al., 1999), answers in questionnaires (Kirby & Maraković, 1996), or bids reported in an auction experiment (Kirby, 1997; Kirby & Maraković, 1995) is realized.

Some studies on human temporal and probabilistic discounting have reported that there is a positive correlation between the temporal and probabilistic discounting rate (Mitchell, 1999; Reynolds, Karraker, Horn, & Richards, 2003; Richards et al., 1999). This means that the temporal and probabilistic discounting are the same process (Rachlin et al., 1991). However, it has also been reported that the reward amount influences the temporal and probabilistic discounting rate in an opposite direction (Green et al., 1999): For the temporal discounting, the larger the reward amount, the lower the discounting rate, on the other hand, for the probabilistic discounting, the larger the reward amount, the higher the discounting rate (Green et al., 1999). This fact means that the temporal and probabilistic discounting are different processes. It is important to notice, however, that the positive correlation between temporal and probabilistic discounting rates and the reward amount effects as stated above have been reported in studies in which participants chose hypothetical rewards or hypothetical rewards with one real reward. In these studies, participants were presented with the delay, probability, and amount of reward as verbal stimuli; they did not learn these parameters through their choice experience.

There have been a few studies on discounting using a choice procedure in which human participants experience delay, probability, and amount of the reward by choosing one of alternatives repeatedly in an experimental session. As far as we know, two studies (Lane, et al., 2003; Rodriguez & Logue, 1988) used the repeated-choice procedures for measuring temporal discounting in adult human participants.

In the contingent condition in Lane et al. (2003), participants were given a choice between a fixed larger amount of money ($0.15) available after a delay varying across six conditions (ranging from 5 s to 90 s) and a variable amount of money that varied across trials (ranging from $0.01 to $0.15) available after a fixed 3-s delay. For each of the delay conditions, the variable amounts of money were presented in either descending or ascending order to obtain indifference points. Participants received total amount of money earned during sessions at the end of each day. Lane et al. (2003) reported that the hyperbolic function was a valid mathematical model for human temporal discounting. However, they did not apply the exponential function to the indifference points. Furthermore, participants did not necessarily learn delay and amount of the reward through their experience of choice trials because these parameter values were presented verbally on the screen of the monitor.

Rodriguez & Logue (1988), using an adjusting-delay procedure, measured delays to the larger reinforcer (adjusting alternative) indifferent with the smaller reinforcer (standard alternative) for adult human participants in Experiments 2 and 3. To obtain the indifference points, the delay value in the adjusting alternative was varied across blocks of trials according to participants' choice: it was increased (decreased) in 1 s when the adjusting (standard) alternative was chosen in two free-choice trials continuously. Reinforcer amount was defined by the length of the reinforcer access period during which participants could earn points exchangeable for money by consummatory responses. The delay value for the standard alternative was varied across five conditions ranging from 2 s to 10 s. To make the delay function as benefit loss, Rodriguez and Logue reduced the points accumulated on the counter in a fixed rate during the delay period. As a result, the indifference points were found to be better described by the hyperbolic function than by the exponential function.

Rodriguez & Logue's (1988) procedure ensures that participants learn the delay and amount of the reinforcers through their experience of repeated choice; however, there might be some problems in the procedure. First, to maximize points, some participants continued to choose the standard alternative until the adjusting-delay was decreased at minimum, and they chose the two alternatives alternately. Use of this strategy causes poor fitness of discounting functions. Second, it is not sure that the reduction of points during the delay period was adequate for examining temporal discounting. Because the reduction rate of points had influence on the indifference points (Rodriguez & Logue, 1988), it is difficult to compare the results among studies in which the reduction rate of reinforcers are not specified.

Different from the previous studies stated above, the present study examined human temporal and probabilistic discounting by using concurrent-chains schedule as a method for measuring discounting and by using choice proportions as a dependent variable. As this choice procedure has been successfully used to investigate humans' impulsiveness or self-control (e.g., Ito & Nakamura, 1998; Logue, Peña-Correal, Rodriguez, & Kabela, 1986), this procedure may also be used to examine temporal and probabilistic discounting

(Davison, 1988). In the present study, relative values of a reinforcer are assumed to be represented by the following choice proportions (cf. Baum & Rachlin, 1969):

$$\frac{B_M}{B_M + B_L} = \frac{V_M}{V_M + V_L} \tag{5}$$

and

$$\frac{B_U}{B_U + B_C} = \frac{V_U}{V_U + V_C} \tag{6}$$

where B_M and B_L are the number of responses to the more and less delayed reinforcers, and V_M and V_L are the discounted values of the more and less delayed reinforcers defined by Equation (1) or (2), respectively. B_U and B_C are the number of responses to the uncertain and certain reinforcers, and V_U and V_C are the discounted values of uncertain and certain reinforcers defined by Equation (3) or (4), respectively.

In the present study, reinforcer amounts were one (A = 1) for both of the alternatives in the delay and probability conditions, delay to the less delayed reinforcer was 2 s, and probability of reinforcement for the certain reinforcer was 1.0. Accordingly, Equation (5) incorporating the hyperbolic and exponential function can be reduced to the Equations (7) and (8), respectively (see Appendix A):

$$\frac{B_M}{B_M + B_L} = \frac{1 + 2k}{2 + (2 + D_M)k}, \tag{7}$$

$$\frac{B_M}{B_M + B_L} = \frac{e^{-kD_M}}{e^{-kD_M} + e^{-2k}}. \tag{8}$$

And Equation (6) incorporating the hyperbolic and exponential function can be reduced to the Equations (9) and (10), respectively (see Appendix B):

$$\frac{B_U}{B_U + B_C} = \frac{1}{2 + h\Theta_U}, \tag{9}$$

$$\frac{B_U}{B_U + B_C} = \frac{e^{-h\Theta_U}}{e^{-h\Theta_U} + 1}. \tag{10}$$

Figure 1 shows theoretical curves derived from Equations (7), (8), (9), and (10). As can be seen, relative values of a reinforcer decrease differently between the hyperbolic and exponential functions with increases in delay (the left panel) and in odds against (the

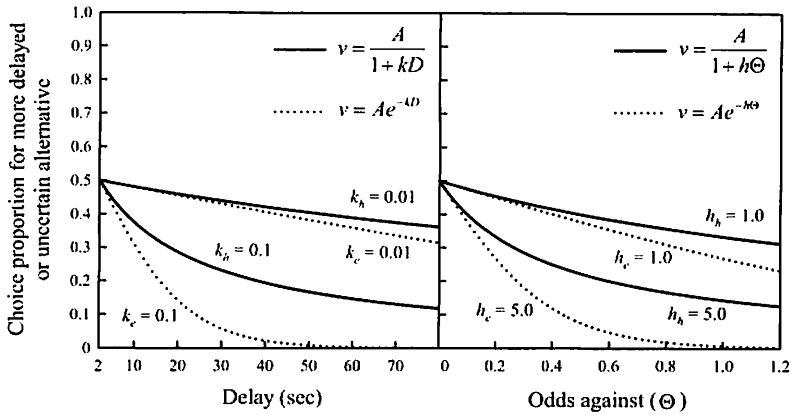

Figure 1. Theoretical curves based on the matching law incorporating the hyperbolic and exponential discounting functions with different parameter values. The right panel shows the probabilistic discounting functions and the left panel shows the temporal discounting functions. k_h and k_e are temporal discounting rate parameters based on Equation (7) and (8), and h_h and h_e are probabilistic discounting rate parameters based on Equation (9) and (10), respectively.

right panel). In general, the exponential functions are steeper than the hyperbolic functions with the same discounting rate for both of the temporal and probabilistic discounting.

For the temporal discounting, it has been reported that the matching law incorporating a variation of the hyperbolic function can describe pigeons' choice between reinforcers with different delays under the concurrent-chains schedules (Davison, 1988; Grace, 1999); however, for the human participants, applicability of the matching law incorporating the hyperbolic function and that incorporating the exponential function has not been examined yet.

The present study, using a concurrent-chains schedule and points as reinforcers later exchangeable for money, examined humans' temporal and probabilistic discounting in terms of the choice proportions, commonly used as a dependent variable in studies of choice, to evaluate whether the results are similar to those obtained when hypothetical rewards or hypothetical rewards with one real reward were used: The temporal and probabilistic discounting are better described by the matching law incorporating the hyperbolic function than that incorporating the exponential function. In addition, the present study examined whether there is a positive correlation between temporal and probabilistic discounting rates (k and h) within participants as reported in previous studies on human discounting (Mitchell, 1999; Reynolds, et al., 2003; Richards et al., 1999) by using the choice situation where participants experience delay, probability, and amount of reinforcer repeatedly. This examination may reveal that the temporal and probabilistic discounting are fundamentally the same process if there is a positive correlation between k and h (cf. Rachlin, Logue, Gibbon, & Frankel, 1986).

METHOD

Participants

The participants were six adult undergraduate students (three males and three females) between 18 and 22 years of age. They were recruited for participation from an introductory psychology class. None of the participants was a psychology major.

Apparatus

The experiment was conducted in a small room (3.6 m by 2.8 m). A 14-inch color CRT monitor with a touch panel (MicroTouch Systems Inc.) was placed on the desk, and was separated by a large panel from a personal computer (NEC PC-9801U2) and the experimenter. The touch panel consisted of a capacitance screen. The minimum detectable response duration was 15 ms and the maximum number of responses that could be detected per second was 44. A touch to the circles presented on the screen of the monitor was defined as a response. A personal computer, programmed to present stimuli (i.e., colored circles and counters) on the screen of the monitor, controlled the experiment and recorded events.

The screen of the monitor contained three colored circles and counters. Two colored circles as alternatives, 5.0 cm in diameter, were located horizontally in the center of the screen and 11 cm apart (from center to center). A small colored circle for the consummatory responses, 3.0 cm in diameter, was located 7.0 cm below the center and 13.5 cm from the sides. A counter was located below each of the large circles and above the small circle. A touch to the circles produced a brief beep as response feedback.

Procedure

Participants were seated in front of the monitor and required to leave all metal objects outside the testing room (i.e., watches and jewelry) to minimize interference with the touch panel during the session. They were then given the following minimal instructions (in Japanese) as to what they were to do:

Please read repeatedly until you understand. Do not ask for additional instructions. You may play a game. Your task is to earn as many points as you can. Points will be accumulated on the counter and you will receive the amounts of money corresponding to the total amount of points accumulated on the counter at the end of the session. You may touch anything on the screen to earn points, but you have to touch with a forefinger. A brief beep sound will be provided if a response is effective. The session will begin when three white circles come on.

A concurrent-chains schedule was employed with two different types of initial-link schedules (i.e., choice phase): The dependent scheduling procedure was used for forced-choice trials, whereas the independent scheduling procedure was used for free-choice trials (Ito, Nakamura, & Kuwata, 1997). For the delay and probability conditions, each session consisted of 20 forced-choice trials followed by 20 free-choice trials. In the baseline condition (explained below), forced-choice trials were omitted.

Figure 2 shows a schematic diagram of the concurrent-chains schedule used for the free-choice trials in the delay condition. During the choice phase, the two larger circles and the one smaller circle with a counter were presented on the screen of the monitor. Each circle was colored with white (the background color of the screen was black). Entry into either of the terminal links was arranged by two independent variable-interval (VI) 30-s VI 30-s schedules for the free-choice trials and by a single VI 15-s schedule for the forced-choice trials. Each interval of the VI schedule was derived from the distribution reported in Fleshler & Hoffman (1962). When each interval in one of the VI schedules timed out, the timer stopped and reinforcement was assigned to the appropriate side. A touch response to the large circle to which the reinforcement was assigned made entry into the terminal links (i.e., delay period). The color of this large circle was changed from white to either blue or yellow, and the other large circle was darkened. A 3-s changeover delay (COD) was used. In this COD procedure, 3 s had to elapse after a changeover response from the right to the left alternative or vice versa before a subsequent response made it possible to enter into the delay period (cf. de Villiers, 1977). The next response to the appropriate circle initiated the delay period defined

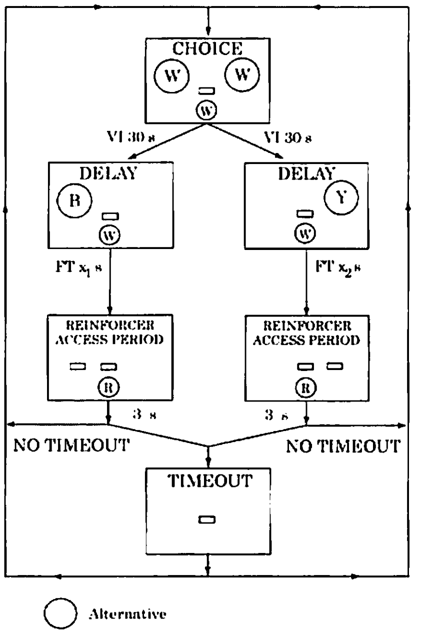

Figure 2. A schematic diagram of the independent scheduling (free choice) procedure used for the delay condition (see text in detail).

by a fixed-time (FT) schedule. For the forced-choice trials, although both alternatives were presented, the available terminal link was assigned quasirandomly to the right or to the left alternative with equal probability (i.e., ten right and ten left alternatives). Responses in the forced trials were never used in data analysis.

After the delay, the reinforcer access period (3 s in duration) was in effect, during which the small circle was colored red, the large circle was darkened, and either the left or the right side counter was presented on the screen for the delay condition (see Figure 2). Each response to the red circle accumulated 1 point (i.e., 1 point was worth 1 yen) on the respective side counter. Therefore, total reinforcer amount (points) per each trial depended on the number of consummatory responses emitted during the 3-s reinforcer access period (Ito & Nakamura, 1998). The center counter accumulated total points earned. The side counter was always reset at the start of the next trial. For the delay condition, to equate overall rates of reinforcement between alternatives, a timeout period followed the reinforcer access period when entry to the terminal link was made from the alternative with the shorter delay (i.e., 2 s). As is shown below, the longer delay was varied from 10 s to 40 s across the delay conditions, therefore, duration of the timeout periods varied from 8 s to 32 s across the conditions. During timeout periods, the screen was darkened except for the center counter, and a touch to the screen produced no scheduled consequences and no feedback beep.

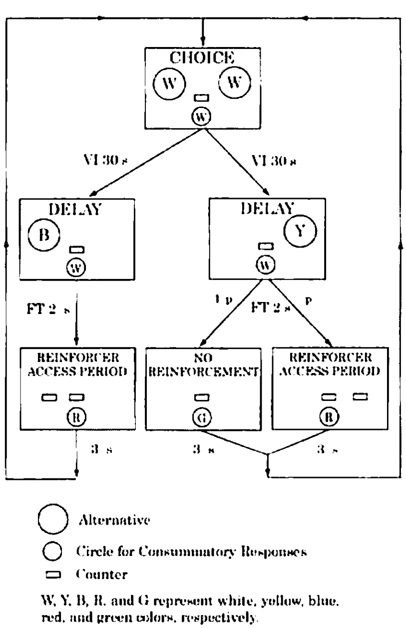

Figure 3. A schematic diagram of the independent scheduling (free choice) procedure used for the probability condition (see text in detail).

Figure 3 shows a schematic diagram of the concurrent-chains schedule used in the probability condition. Arrangements of reinforcement schedules for the initial link were the same as in the delay condition. FT values in the terminal link were 2 s for both of the alternatives. The reinforcer access period for the uncertain alternative depended on a prescribed probability of reinforcement. When the reinforcer access period was presented after the delay period, the same events as in the delay conditions occurred. In contrast, when the reinforcer access period was not presented, the small circle was colored green for 3 s, and responses to the circle produced no scheduled consequences (see

Figure 3).

The experiment consisted of three conditions, that is, baseline, delay, and probability conditions. In the baseline condition, reinforcer amount was 1 point and reinforcer delay was 2 s for both alternatives. The baseline condition was presented once, but it was replicated if the participant was not indifferent between the two alternatives. Indifference was defined as choice proportions ranging from .55 to .45. For the delay condition, three different pairs of reinforcer delays (2 s vs. 10 s, 2 s vs. 20 s, and 2 s vs. 40 s) were studied with equal probabilities of 1.0. For the probability condition, three different pairs of reinforcer probabilities (1.0 vs. .90, 1.0 vs. .80, and 1.0 vs. .65) were studied with equal delays of 2 s. For the delay and probability conditions, each condition was presented twice in successive two sessions and in a quasirandom sequence (as shown in Table 1). Based on the previous studies using the choice procedure similar to the present study (Ito & Nakamura, 1998; Ito et al., 1997), it was thought that the amount of sessions in the present study was enough for the participants' choice responses to be stable.

The side to which the variable alternative was assigned was fixed for each participant and counterbalanced across the participants. Four or five sessions were conducted per day, and the experiment was conducted over three days.

RESULTS

Table 1 shows the number of responses to both left and right circles, choice proportions, and the order of conditions for each participant. Temporal and probabilistic discounting rates estimated from the matching law incorporating the hyperbolic (Equations [7] and [9]) or the exponential (Equations [8] and [10]) function, and coefficients of determination (r^2) for each participant are also shown in Table 1. Data were based on the last session for each of the three conditions. Choice proportions were obtained by dividing the number of initial-link responses to the more delayed or the uncertain alternative by the total number of initial-link responses. Choice proportions generally decreased with increase in delay or decrease in probability.

Best-fitting functions derived from the matching law incorporating the hyperbolic and exponential function are examined (see Table 1). As for the temporal discounting, the coefficient of determination ranged from .35 to .99 for Equation (7), whereas it ranged from .16 to .94 for Equation (8). Although there were substantial individual differences, median values of the coefficients of determination across the six participants were .74 and

Table 1. Sequence of conditions, number of initial-link responses, mean choice proportion, number of sessions, estimated discounting rates (k and h) based on the matching law incorporating the hyperbolic (Hyp.) and exponential (Exp.) functions, and coefficients of determination (r^2) for each participant.

					Choice		Temporal discounting				Probabilistic discounting			
				Initial-link	proportion		Hyp.		Exp.		Hyp.		Exp.	
Partici-pant	Order	Delay (sec) Left / Right	Probability Left / Right	responses Left / Right	for variable alternative	Sessions	k	r^2	k	r^2	h	r^2	h	r^2
S1	1	2 / 2	1.0 / 1.0	297 / 327	0.524	1	0.042	0.35	0.023	0.16	1.358	0.77	1.027	0.70
	5	2 / 10	1.0 / 1.0	656 / 471	0.418	2								
	3	2 / 20	1.0 / 1.0	824 / 279	0.253	2								
	6	2 / 40	1.0 / 1.0	335 / 211	0.386	2								
	7	2 / 2	1.0 / 0.90	300 / 220	0.423	2								
	2	2 / 2	1.0 / 0.80	342 / 254	0.426	2								
	4	2 / 2	1.0 / 0.65	307 / 189	0.381	2								
S2	1	2 / 2	1.0 / 1.0	435 / 455	0.511	3	0.056	0.74	0.034	0.84	1.702	0.43	1.250	0.41
	2	2 / 10	1.0 / 1.0	634 / 489	0.435	2								
	6	2 / 20	1.0 / 1.0	799 / 632	0.442	2								
	4	2 / 40	1.0 / 1.0	1378 / 266	0.162	2								
	3	2 / 2	1.0 / 0.90	702 / 406	0.366	2								
	7	2 / 2	1.0 / 0.80	597 / 540	0.475	2								
	5	2 / 2	1.0 / 0.65	905 / 454	0.334	2								
S3	1	2 / 2	1.0 / 1.0	1120 / 1048	0.517	1	10.000	0.99	0.190	0.93	13.290	0.88	6.467	0.84
	5	10 / 2	1.0 / 1.0	319 / 1843	0.148	2								
	7	20 / 2	1.0 / 1.0	283 / 2694	0.095	2								
	3	40 / 2	1.0 / 1.0	177 / 2614	0.063	2								
	2	2 / 2	0.90 / 1.0	666 / 1255	0.347	2								
	4	2 / 2	0.80 / 1.0	268 / 2415	0.100	2								
	6	2 / 2	0.65 / 1.0	336 / 1977	0.145	2								
S4	1	2 / 2	1.0 / 1.0	721 / 837	0.537	1	0.281	0.74	0.079	0.40	4.252	0.81	2.421	0.76
	5	2 / 10	1.0 / 1.0	317 / 105	0.249	2								
	7	2 / 20	1.0 / 1.0	399 / 64	0.138	2								
	3	2 / 40	1.0 / 1.0	452 / 145	0.243	2								
	4	2 / 2	1.0 / 0.90	310 / 156	0.335	2								
	2	2 / 2	1.0 / 0.80	1170 / 733	0.385	2								
	6	2 / 2	1.0 / 0.65	421 / 121	0.223	2								
S5	1	2 / 2	1.0 / 1.0	725 / 737	0.504	2	0.028	0.67	0.021	0.76	1.534	0.62	1.249	0.69
	7	2 / 10	1.0 / 1.0	760 / 711	0.483	2								
	2	2 / 20	1.0 / 1.0	811 / 771	0.487	2								
	5	2 / 40	1.0 / 1.0	1204 / 425	0.261	2								
	6	2 / 2	1.0 / 0.90	758 / 651	0.462	2								
	4	2 / 2	1.0 / 0.80	771 / 799	0.509	2								
	3	2 / 2	1.0 / 0.65	368 / 154	0.295	2								
S6	1	2 / 2	1.0 / 1.0	161 / 161	0.500	1	0.065	0.88	0.036	0.94	5.938	0.94	3.190	0.96
	3	10 / 2	1.0 / 1.0	637 / 685	0.482	2								
	5	20 / 2	1.0 / 1.0	531 / 1124	0.321	2								
	7	40 / 2	1.0 / 1.0	204 / 816	0.200	2								
	4	2 / 2	0.90 / 1.0	302 / 522	0.367	2								
	6	2 / 2	0.80 / 1.0	260 / 526	0.331	2								
	2	2 / 2	0.65 / 1.0	170 / 932	0.154	2								

.80 for Equations (7) and (8), respectively. The discounting rate (k) ranged from 0.028 to 10.0 (Mdn = 0.061) for Equation (7), and it ranged from 0.021 to 0.190 (Mdn = 0.035) for Equation (8), respectively.

As for the probabilistic discounting, the coefficient of determination ranged from .43 to .94 for Equation (9), whereas it ranged from .41 to .96 for Equation (10). Median values across the six participants were .79 and .73 for Equations (9) and (10), respectively. The discounting rate (h) ranged from 1.358 to 13.29 (Mdn = 2.977) for Equation (9), and it ranged from 1.027 to 6.467 (Mdn = 1.836) for Equation (10), respectively.

Figure 4 shows the median choice proportions for the more delayed (the left panel) or the uncertain (the right panel) alternative. The best-fitting functions derived from the matching law incorporating the discounting functions are represented by solid (the hyperbolic function) and dotted (the exponential function) curves, respectively. For the temporal discounting, coefficients of determination were .96 and .93 for Equations (7) and (8), respectively. For the probabilistic discounting, coefficients of determination were .82 and .79 for Equations (9) and (10), respectively. These results revealed that temporal and probabilistic discounting processes were somewhat better described by the matching law with the hyperbolic functions than that with the exponential functions. However, the paired t test revealed that there were no significant differences in the coefficient of determination between the matching law incorporating the hyperbolic and exponential functions, t (5) = 0.78, p > .05 for the temporal discounting and t (5) = 0.70, p > .05 for the probabilistic discounting, respectively.

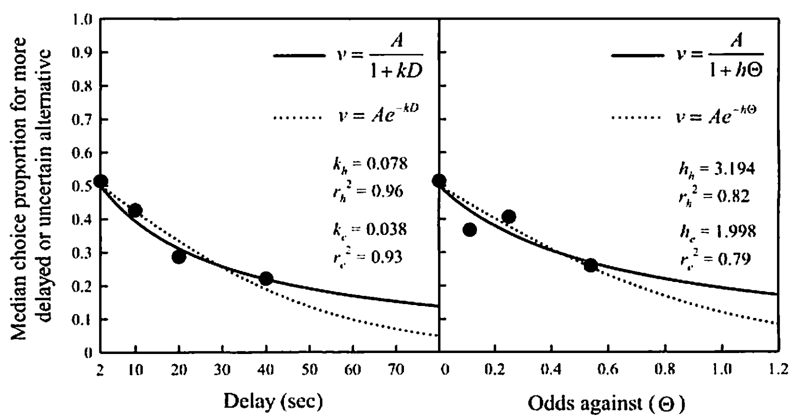

Figure 4. Median choice proportions for the more delayed or uncertain reinforcer as a function of delay or odds against. The solid and dotted lines show the best-fitting curves for the matching law incorporating the hyperbolic and exponential functions. k_h and k_e are temporal discounting rate parameters estimated by Equation (7) and (8), and h_h and h_e are probabilistic discounting rate parameters estimated by Equation (9) and (10), respectively.

Figure 5 shows the correlation between the temporal and probabilistic discounting rates (k and h) within participants, based on the matching law incorporating the hyperbolic and exponential functions. As shown in Figure 5, the probabilistic discounting rate increases as the temporal discounting rate increases. A linear regression was applied to the log-

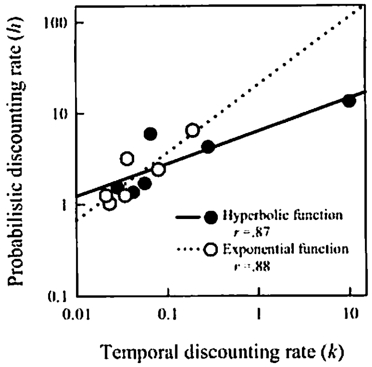

Figure 5. A scatter plot of log-transformed temporal discounting rate parameters (*k*) versus log-transformed probabilistic discounting rate parameters (*h*). Each data point represents the value of *h* for the probability condition as a function of the value of *k* for the delay condition for an individual participant. The filled and open circles show the discounting rates based on the matching law incorporating the hyperbolic and exponential functions, respectively. The solid and dotted lines show the least-squares fit to the data.

transformed data. This procedure yielded the correlation coefficients and the equations for the best-fitting straight lines, $r = 0.87$ ($y = 0.36x + 0.80$) for the hyperbolic discounting rate and $r = 0.88$ ($y = 0.74x + 1.31$) for the exponential discounting rate. There were significant positive correlations between temporal and probabilistic discounting rates, $t(4) = 3.32$, $p < .05$ for the hyperbolic function and $t(4) = 3.77$, $p < .05$ for the exponential function, respectively. Thus, participants who showed larger discounting rates for delayed reinforcers also showed larger discounting rates for probabilistic reinforcers.

The mean number of consummatory responses to the small red circle per reinforcement did not differ substantially between the two alternatives for all conditions: Mean number of consummatory responses across all conditions was 20.6 for the left alternative and 19.9 for the right alternative, respectively. Mean ratios of obtained points between the two alternatives, averaged over all participants and across conditions, were .99 for the delay condition, and .99 for the probability condition. Thus, the ratios of obtained points between the two alternatives were close to the programmed ratio of 1.0.

DISCUSSION

The present study examined human temporal and probabilistic discounting in choice situations where participants chose between less and more delayed reinforcers and chose between certain and uncertain reinforcers repeatedly under concurrent-chains schedules.

Based on these choice procedures, the present study demonstrated that the discounting of delayed and probabilistic reinforcers could be examined by using choice proportions as a dependent variable and by applying the matching law incorporating the hyperbolic function and that incorporating the exponential function.

The results from group medians (Figure 4) indicate that, for delays and probabilities used in the present study, temporal and probabilistic discounting were well described by both hyperbolic and exponential functions incorporated into the matching law, although there were only four data points. These results are in part inconsistent with the results of previous studies using hypothetical rewards (Myerson & Green, 1995; Rachlin et al., 1991), hypothetical rewards with one real reward (Kirby & Maraković, 1996; Richards et al., 1999), and real rewards (Rodriguez & Logue, 1988, Experiments 2 and 3).

Several factors seem to be responsible for the difference in results between the present study and previous studies on temporal and probabilistic discounting. First, ranges of delays and probabilities used in the present study (i.e., delays ranging from 2s to 40 s and probabilities ranging from 1.0 to .65) were narrower than that used in previous studies. For example, ranges of delays used in previous studies were, from 1 month to 50 years (Rachlin, et al., 1991), from 3 to 29 days (Kirby & Maraković, 1995), and from 0 to 365 days (Richards et al., 1999). And ranges of probabilities used in previous studies were, from 0.95 to 0.05 (Green et al., 1999; Rachlin et al., 1991) and from 1.0 to 0.25 (Richards et al., 1999). As shown in Figure 1, at brief delays and at high probabilities (low odds against), the two theoretical curves derived from the matching law incorporating the hyperbolic and exponential functions are close, whereas they differentiate at long delays and at low probabilities (high odds against). Accordingly, the narrow range of delays and probabilities used in the present study may account for the reason that there was little difference in the coefficients of determination between the matching law incorporating the hyperbolic and exponential functions.

Other possible reasons that can be responsible for the difference in results between the present and previous studies are, difference in choice procedure used (concurrent-chains schedules under which participants learn delay, probability, and amount of reinforcers vs. discrete-choice procedures in which rewards are presented as verbal stimuli), the dependent variable (choice proportion vs. indifference point), type of reward (points exchangeable for money vs. hypothetical monetary rewards or that with one real reward). In any case, we can say that the present results are consistent with previous studies in that the hyperbolic function fits the data well.

For the temporal discounting, present results can be compared with results from previous studies measuring humans' choice between equal amounts of reinforcer with different delays under concurrent-chains schedules (Ito & Nakamura, 1998; Logue et al., 1986). In Experiment 3 in Logue et al. (1986) and in Experiment 1 in Ito & Nakamura (1998), participants were exposed to a concurrent-chains schedule in which two independent VI 30 s schedules were arranged for the initial links and FT schedules were arranged for the terminal links. Consummatory responses were needed for the participants to receive points exchangeable for money after the session. In Logue et al. (1986), FT values were varied across conditions: 6 s vs. 6 s, 10 s vs. 2 s, 1 s vs. 11 s, 2 s vs. 10 s, 11 s vs. 1 s. In Ito & Nakamura (1998), the FT value was fixed at 5 s in the one alternative and it was varied in the other alternative across conditions (i.e., 5 s, 25 s, 50 s, and 100 s). The matching law incorporating the hyperbolic function (Equation [7]) and that incorporating the exponential function (Equation [8]) were fitted to the choice proportion reported in Logue et al. (1986) and Ito & Nakamura (1998), and estimated temporal discounting rates.

As a result, temporal discounting rates estimated by fitting Equation (7) to each participant's choice proportion data were, 0.069, 0.097, 0.142, and 1.626 (*Mdn* = 0.120) for Logue et al.'s (1986) data, and, 0.006, 0.008, 0.047, 0.085, and 0.110 (*Mdn* = 0.047) for Ito & Nakamura's (1998) data, respectively (An outlier obtained from S82 in Ito & Nakamura, indicating the discounting rate more than 100,000, was omitted). Except for the outlier, these values are comparable with temporal discounting rates obtained from the present study. Discounting rates obtained from Logue et al's (1986) data seem to be somewhat higher than that obtained from Ito & Nakamura (1998) and present study. It might be the reason that, in Logue et al. (1986), timeout periods were not used to equate reinforcement rates between alternatives; therefore, participants tended to show greater preference for the less delayed reinforcer, resulting in the higher discounting rates.

The present study found a positive correlation between temporal and probabilistic discounting rates. This result is consistent with that in the previous studies using hypothetical rewards with one real reward (Mitchell, 1999; Reynolds et al., 2003; Richards et al., 1999). Although there are procedural differences between the present and previous studies, this fact suggests that the temporal and probabilistic discounting are fundamentally same process (Green & Myerson, 1996; Rachlin et al., 1986, 1991). For example, Rachlin et al. (1991) proposed that, in a repeated-gambles situation, probability of wins can be viewed as the expected waiting time until a win; therefore, probabilistic rewards are discounted in the same way as delayed rewards. Similarly, Green & Myerson (1996) suggested that delay can be viewed as the expected odds against because delayed rewards can be judged to be uncertain; therefore, delayed rewards are discounted in the same way as probabilistic rewards. In any case, it seems that delayed and probabilistic rewards affect behavior in similar ways.

Green et al. (1999) found that temporal and probabilistic discounting rate varied in opposite directions as a function of reward amount. This result contradicts the notion that temporal and probabilistic discounting are the same process, because any factor having effects on the temporal discounting must have the same effects on the probabilistic discounting if they are the same process. However, the opposite effect of reward amount on the temporal and probabilistic discounting has been reported in studies using hypothetical rewards presented as verbal stimuli and using indifference points as a dependent variable (Green et al., 1999). Therefore, additional studies are needed to examine the effect of amount of delayed and probabilistic rewards using repeated-choice situations as used in the present study.

APPENDIX A

For temporal discounting, based on the hyperbolic function (Equation [1]), taking Equation (1) at the right hand of Equation (5) yields:

$$\frac{B_M}{B_M + B_L} = \frac{V_M}{V_M + V_L} = \frac{\dfrac{A_M}{1 + kD_M}}{\dfrac{A_M}{1 + kD_M} + \dfrac{A_L}{1 + kD_L}}, \qquad \text{(A1)}$$

where A_M and A_L are the reinforcer amounts to the more and less delayed reinforcers, and D_M and D_L are the delays to the more and less delayed reinforcers, respectively. Assuming that $A_M = A_L$ and that $D_L = 2$ s as used in the present study, rearranging Equation (A1) results in Equation (7).

On the other hand, based on the exponential function (Equation [2]), taking Equation (2) at the right hand of Equation (5) yields:

$$\frac{B_M}{B_M+B_L}=\frac{V_M}{V_M+V_L}=\frac{A_M e^{-kD_M}}{A_M e^{-kD_M}+A_L e^{-kD_L}}. \quad \text{(A2)}$$

Assuming that $A_M = A_L$ and that $D_L = 2$ s as used in the present study, rearranging Equation (A2) results in Equation (8).

APPENDIX B

For probabilistic discounting, based on the hyperbolic function (Equation [3]), taking Equation (3) at the right hand of Equation (6) yields:

$$\frac{B_U}{B_U+B_C}=\frac{V_U}{V_U+V_C}=\frac{\dfrac{A_U}{1+h\Theta_U}}{\dfrac{A_U}{1+h\Theta_U}+\dfrac{A_C}{1+h\Theta_C}}, \quad \text{(B1)}$$

where A_U and A_C are the reinforcer amounts to the uncertain and certain reinforcers, and Θ_U and Θ_C are the odds against receipt of the uncertain and certain reinforcers, respectively. Assuming that $A_U = A_C$ and that $\Theta_C = 0$ (i.e., $p = 1.0$) as used in the present study, rearranging Equation (B1) results in Equation (9).

On the other hand, based on the exponential function (Equation [4]), taking Equation (4) at the right hand of Equation (6) yields:

$$\frac{B_U}{B_U+B_C}=\frac{V_U}{V_U+V_C}=\frac{A_U e^{-h\Theta_U}}{A_U e^{-h\Theta_U}+A_C e^{-h\Theta_C}}. \quad \text{(B2)}$$

Assuming that $A_U = A_C$ and that $\Theta_C = 0$ as used in the present study, rearranging Equation (B2) results in Equation (10).

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選択場面における選択率から導出されたヒトの遅延割引と確率割引

佐 伯 大 輔　　伊 藤 正 人

実験参加者に選択肢を複数回経験させることにより遅延時間と確率を学習させる場面を用いた遅延割引や確率割引の研究は、これまで余りなされてこなかった。本研究では、並立連鎖スケジュールを用いて、成人 6 名の遅延割引と確率割引を測定した。選択期には変動間隔スケジュールが配置され、結果受容期では、得点呈示に関する遅延時間や確率が操作された。また、結果受容期では、実験後に換金可能な得点を獲得するために完了反応が必要とされた。各参加者は、 4 条件の遅延条件（ 2 秒対 2 秒から 2 秒対40秒）と 4 条件の確率条件（1.0対1.0から1.0対.65）を経験した。その結果、遅延割引と確率割引は、双曲線関数や指数関数を組み込んだ対応法則によりうまく記述できた。さらに、遅延割引率と確率割引率の間には、有意な正の相関が見られた。この結果は、遅延割引と確率割引が同様の過程であることを示唆する。

キーワード：選択、遅延割引と確率割引、並立連鎖スケジュール、スクリーンへのタッチ反応、ヒト