

*DETERMINATION OF DISCOUNT FUNCTIONS IN  
RATS WITH AN ADJUSTING-AMOUNT PROCEDURE*

JERRY B. RICHARDS, SUZANNE H. MITCHELL,  
HARRIET DE WIT, AND LEWIS S. SEIDEN

UNIVERSITY OF CHICAGO

An adjusting-amount procedure was used to measure discounting of reinforcer value by delay. Eight rats chose between a varying amount of immediate water and a fixed amount of water given after a delay. The amount of immediate water was systematically adjusted as a function of the rats' previous choices. This procedure was used to determine the indifference point at which each rat chose the immediate amount and the delayed amount with equal frequency. The amount of immediate water at this indifference point was used to estimate the value of the delayed amount of water. In Experiment 1, the effects of daily changes in the delay to the fixed reinforcer (100  $\mu$ l of water delivered after 0, 2, 4, 8, or 16 s) were tested. Under these conditions, the rats reached indifference points within the first 30 trials of each 60-trial session. In Experiment 2, the effects of water deprivation level on discounting of value by delay were assessed. Altering water deprivation level affected the speed of responding but did not affect delay discounting. In Experiment 3, the effects of varying the magnitude of the delayed water (100, 150, and 200  $\mu$ l) were tested. There was some tendency for the discounting function to be steeper for larger than for smaller reinforcers, although this difference did not reach statistical significance. In all three experiments, the obtained discount functions were well described by a hyperbolic function. These experiments demonstrate that the adjusting-amount procedure provides a useful tool for measuring the discounting of reinforcer value by delay.

*Key words:* choice, self-control, impulsivity, delayed reinforcement, reinforcer magnitude, nose poke, rat

---

The experiments reported in this paper use an adjusting procedure to measure discounting of reinforcer value by delay. This test procedure is patterned after one developed by Mazur (1987) to measure the effects of delay and uncertainty on reinforcer value (Mazur, 1989, 1991, 1995). Mazur has called his procedure the adjusting-delay procedure because the delay to a small reinforcer is adjusted until the subjects choose the small reinforcer and the more delayed, larger reinforcer with equal frequency. It is assumed that, at the *indifference point*, the reinforcing effectiveness (or subjective values) of the small reinforcer presented after a short delay and the larger reinforcer presented after a longer delay are equivalent. We present here a variation of Mazur's procedure called the adjusting-amount procedure because the animal adjusts the amount of reinforcer.

---

The authors thank Guillermo Ramirez, Brian Carlson, and Marcus Chock for assistance in conducting the study. This research was supported by Grants MH-11191 and DA-10588.

Correspondence concerning this article should be addressed to Jerry B. Richards, University of Chicago, Department of Pharmacological and Physiological Sciences, 947 East 58th Street, Chicago, Illinois 60637.

The adjusting-amount procedure is analogous to a psychophysical procedure, and is specifically designed to measure reinforcer value. In humans, the psychophysical method of adjustment is used to determine discriminative sensitivity by presenting subjects with a standard stimulus and then asking them to adjust another stimulus until it matches the standard stimulus (Stevens, 1975). In the experiments described in this paper, we use a similar procedure to determine the value of reinforcers for rats. The rats are given a choice between a delayed, large-magnitude reinforcer and a reinforcer of adjusting magnitude that is presented immediately. The standard reinforcer (analogous to the standard stimulus in the human psychophysics preparation above) is held constant within a session while the magnitude of the adjusting reinforcer is systematically varied across trials as a function of the rat's choices. The term *standard* is used to refer to the fixed reinforcer, and *adjusting alternative* is used to refer to the alternative reinforcer of varying magnitude in the discussion that follows.

Across successive trials, the magnitude of the adjusting alternative is increased after the animal chooses the standard and is decreased

after the animal chooses the adjusting reinforcer. When the rat chooses the standard and the adjusting reinforcers with equal frequency, we infer that the reinforcing value of the adjusted reinforcer matches the value of the standard. This point is referred to as the indifference point and provides the measure of the value of the standard.

For example, a thirsty rat may be given a choice between 100  $\mu$ l of water presented after an 8-s delay (standard) and smaller amounts of water presented immediately (adjusting alternative). If the animal chooses the standard, the amount of water available as the adjusting alternative on the next trial is increased by 10%. Conversely, if the animal chooses the adjusting alternative, the amount of water available as the adjusting alternative on the next trial is decreased by 10%. The amount of immediate water is adjusted from trial to trial in this manner until the rat chooses the standard (100  $\mu$ l of water delayed by 8 s) and adjusting alternative (immediate water) with equal frequency (this is assumed to be an indifference point). The amount of immediate water chosen by the rat at the indifference point is taken as the measure of the value of the standard.

The indifference points for a series of standards can be used to produce discount curves that describe the rate at which the value of a particular reinforcer decreases as a function of increases in some dimension, such as delay to reinforcement. The effects of delay on reinforcer value have been studied in humans (e.g., Green, Fry, & Myerson, 1994; Rachlin, Raineri, & Cross, 1991), pigeons (e.g., Mazur, 1987), and rats (e.g., Bradshaw & Szabadi, 1992). In all three species, the curves that result from the devaluation of reinforcer value by delay are well described by the hyperbolic function of Mazur (1987):

$$V = bA/(1 + kD), \quad (1)$$

where  $V$  is the value of the delayed reinforcer,  $A$  is the amount of the reinforcer,  $D$  is the length of the delay,  $k$  is a free parameter that describes the steepness of the discount function, and  $b$  is a free parameter representing bias for either the standard or the adjusting alternative that is independent of the delay associated with the standard reinforcer. Larger values of  $k$  indicate that the rats discount

the value of the delayed reinforcer more rapidly.

The most important difference between the adjusting-amount procedure and Mazur's (1987) adjusting-delay procedure is that in Mazur's procedure delay to the reinforcer is adjusted, whereas in the adjusting-amount procedure reinforcer amount (i.e., amount of water) is adjusted. Thus, using the adjusting-amount procedure, the value of 100  $\mu$ l of water delayed by 8 s is measured in terms of microliters of immediate water. In Mazur's adjusting-delay procedure, the rat is given a choice between two reinforcer amounts (determined by the experimenter), and the pattern of choices causes the delay to the larger one to adjust upward or downward. The result is a delay duration at which the value of the larger reinforcer equals that of the smaller reinforcer. In the adjusting-amount procedure, value is indicated by an amount of immediate water, whereas in the adjusting-delay procedure, value is indicated by a delay duration. The adjusting-amount procedure used here also differed from Mazur's application of the adjusting-delay procedure in how the standard was changed. Mazur held the standard (delay to the reinforcer) constant for many sessions before a determination of the discounted value was made. In the present study the standard was changed daily. Changing the standard daily permits a more rapid determination of the discount function. Using the adjusting-amount procedure in conjunction with daily changes in the standard allowed five data points that described an individual rat's discount function to be determined in a single week.

Three experiments tested the ability of the adjusting-amount procedure to rapidly generate discount functions under a variety of test conditions. In Experiment 1, the adjusting-amount procedure was used to determine discount functions for 100  $\mu$ l of water presented after delays of 0, 2, 4, 8, and 16 s. The delays were changed daily so that five standards were tested each week. We anticipated that, for the different standards (i.e., delays), the amount of immediate water at which the rats chose the adjusting alternative and the standard equally often would decrease as the delay associated with the standards increased.

## EXPERIMENT 1

*Method*

**Subjects.** Eight Sprague-Dawley rats (Holtzman), weighing between 350 and 400 g at the beginning of training, were used. The rats were housed 2 per cage in hanging stainless-steel wire cages. Lights were on in the colony room from 7:00 a.m. to 7:00 p.m. Food (4% Teklad rat chow) was available ad lib. On the training days (Monday through Friday), the rats received 20-min access to water at the end of the testing session. On nontraining days (Saturday and Sunday), the rats were given 20-min access to water between 10:00 a.m. and 2:00 p.m.

**Apparatus.** Eight locally constructed experimental chambers were used. The chambers had stainless-steel grid floors, aluminum front and back walls, Plexiglas sides, and a Plexiglas top. The test chambers were 20 cm by 22 cm by 23 cm (inside dimensions). The front wall served as the test panel. As shown in Figure 1, the test panel had two water dispensers (4 cm diameter) located on either side of a centrally located snout-poke hole (2.5 cm diameter). The water dispensers were centered 2.5 cm above the floor and 5 cm from the closest side wall of the chamber. Stimulus lights were mounted above the two water dispensers and the center snout-poke hole. The center stimulus light was positioned directly above the center snout-poke hole, 7 cm from the floor and 11.5 cm from the side walls. The stimulus lights for each water dispenser were positioned 5.5 cm above the floor of the chamber and 2 cm from the closest side wall. The water dispenser stimulus lights were arranged so that they were level with the rat's eyes when the rat's snout interrupted an infrared beam in the center snout-poke hole. A Sonalert® tone generator with a frequency of 4,500 cps was mounted above the left stimulus light 9 cm from the floor and 3 cm from the left side of the chamber. Snout pokes and head entries into the water dispensers were monitored with infrared detectors located 0.5 cm behind the front panel. The water dispensers consisted of 28-V solenoid valves (General Valve Corporation; Model 3-424-900) each attached to a separate 600- to 800-ml reservoir with 20-mm PVC tubing. The solenoid valves had two output ports, a normally open port and a normally closed port. Water was dis-

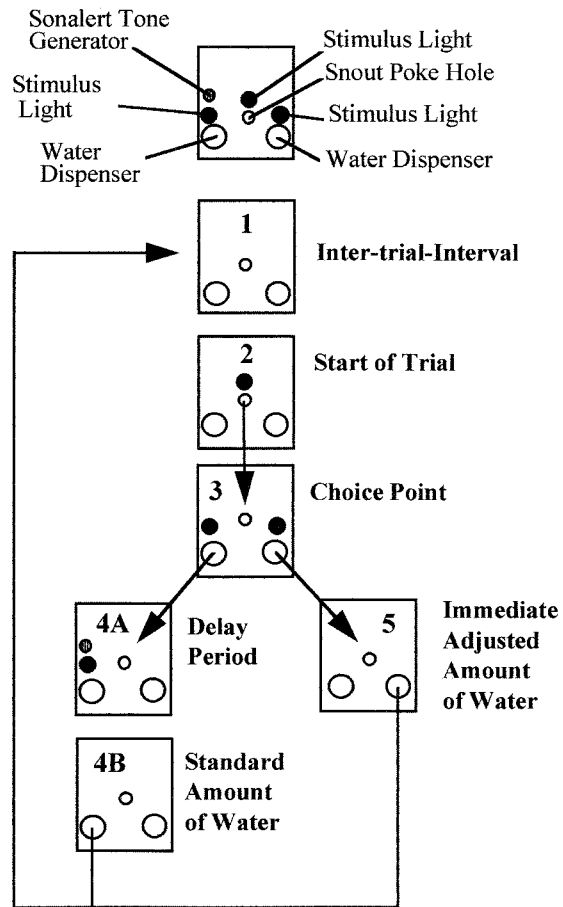


Fig. 1. A schematic illustration of the phases of the adjusting-amount procedure in Experiment 1. Panels 1 through 5 indicate when the various stimuli were turned on during the different phases of the test procedure. A darkened stimulus marker shows that the stimulus is on. See text for explanation.

pensed through the normally closed port. The normally open port allowed release of trapped air between operations of the solenoid. Operation of the solenoid valve caused water to drip into a Plexiglas bowl through a spout made of 18-gauge tubing. Access to the Plexiglas bowl was arranged so that the rat could easily reach the water with its tongue but could not interfere with the falling water drop with its snout. Each water dispenser was calibrated to provide a flow rate of 1.5  $\mu$ l per centisecond by adjusting the amount of water in the reservoir. The amount of water dispensed to the rat was a linear function of the duration for which the solenoid valve was held open. The equation  $y = 1.5x - 2.9$  pre-

dicted the amount of water dispensed, where  $y$  was the amount in microliters and  $x$  was the solenoid operation duration in centiseconds. For example, opening the valve for 25, 69, and 135 centiseconds dispensed 35, 100, and 200  $\mu$ l of water, respectively. An audible click accompanied each opening and closing of the valve. The large size of the reservoir (600 to 800 ml) insured that the flow rate was not appreciably altered by the decreasing water level during an experimental session. In general, less than 10 ml of water was dispensed from a single dispenser during an experimental session. Distilled water was used to prevent build-up of mineral deposits in the valves and tubing, which could alter performance over time. The water dispensers were tested weekly and were adjusted if the obtained drop size deviated from the predicted drop size by more than 5%.

The eight chambers were connected to a 33-MHz 486DX microcomputer using a MED Associates interface. The experimental contingencies were programmed using the MED-PC<sup>®</sup> programming language. The temporal resolution of the system was 0.01 s.

**Procedure.** The adjusting-amount procedure used in Experiment 1 is outlined in Figure 1. Each session consisted of 60 discrete choice trials plus a variable number of forced trials. Each trial was separated by an intertrial interval (ITI). The total time between the start of each trial was 30 s plus the time taken for the rat to make a choice response. During the ITI all of the stimuli in the chamber were off (Figure 1, Panel 1). The start of each trial was signaled by turning on the light above the center snout-poke hole (Figure 1, Panel 2). The first response (snout poke) to the center hole after the beginning of a trial caused the stimulus light above the center hole to be turned off and the stimulus lights above the left and right water dispensers to be turned on (Figure 1, Panel 3). The rat was then required to choose between the left and right water dispensers. The standard was always presented on the left side. Inserting the head into this dispenser resulted in the delayed delivery of 100  $\mu$ l of water. The adjusting amount of water was always presented on the right side. Inserting the head into this dispenser resulted in the immediate delivery of a variable amount of water.

When the animal chose the standard, the

light above the adjusting alternative was turned off and a tone was turned on (Figure 1, Panel 4A). This tone remained on throughout the delay period. At the end of the delay, a 100- $\mu$ l drop of water was delivered and the tone was turned off for the remainder of the 30 s trial (Figure 1, Panel 4B). Note that when the rat chose the standard, the ITI duration was 30 s minus the delay associated with that reinforcer. When the rat chose the immediate alternative, the ITI duration was 30 s.

When the animal chose the adjusting alternative, an amount of water was delivered immediately and the stimulus lights above the left and right water dispenser apertures were turned off for the remainder of the 30 s (Figure 1, Panel 5). During each session, the amount of water available on the adjusting alternative was systematically varied. If the animal chose the standard, the amount delivered on the adjusting alternative was increased by 10% on the next trial. If the animal chose the adjusting alternative, the amount delivered on the adjusting alternative was decreased by 10% on the next trial.

Forced trials were used to insure that the rats were exposed to the consequences of choosing both the delayed 100- $\mu$ l amount of water from the standard and the immediate adjusted amount of water from the adjusting alternative. Choice of either the standard or the adjusting alternative on two consecutive trials was followed by a forced trial in which the rat was required to choose the opposite side. On forced trials only the stimulus light above the required alternative was turned on after the central snout-poke response. Responses to the nonilluminated side had no programmed effect.

Five experimental sessions were conducted each week. The standard delay to the reinforcer was constant during each session but changed between the daily sessions in a pseudorandom fashion, as shown in Table 1. The delay durations were 0, 2, 4, 8, and 16 s. The sequence of delays was arranged so that in a 5-week period, each delay was presented following the other four delays at least once. In addition, each delay value was tested on each of 5 possible days of the week. For each delay, the amount of water available on the adjusting alternative at the beginning of the session was set at high (71  $\mu$ l) and low (35  $\mu$ l)

Table 1

Sequence of delays associated with the standard in Experiment 1.

	Training day				
	Mon	Tues	Wed	Thurs	Fri
Week 1	8 <sub>lo</sub>	0 <sub>lo</sub>	4 <sub>lo</sub>	2 <sub>hi</sub>	16 <sub>hi</sub>
Week 2	2 <sub>lo</sub>	4 <sub>hi</sub>	16 <sub>lo</sub>	0 <sub>hi</sub>	8 <sub>hi</sub>
Week 3	0 <sub>lo</sub>	16 <sub>hi</sub>	8 <sub>lo</sub>	4 <sub>lo</sub>	2 <sub>hi</sub>
Week 4	4 <sub>hi</sub>	8 <sub>hi</sub>	2 <sub>lo</sub>	16 <sub>lo</sub>	0 <sub>lo</sub>
Week 5	16 <sub>hi</sub>	2 <sub>hi</sub>	0 <sub>lo</sub>	8 <sub>lo</sub>	4 <sub>lo</sub>

*Note.* Hi indicates that the amount of water available on the adjusting side at the beginning of the test session was 71  $\mu$ L. Lo indicates that the adjusting side started at 35  $\mu$ L. At the end of 5 weeks the same sequence was repeated but the hi and lo starting amounts were reversed.

amounts on alternate tests of that particular delay (see Table 1).

The median drop size (in microliters of immediate water) for the last 30 choice trials of each 60-trial session was used as the estimate of the indifference point (i.e., the value of

the delayed reinforcer). The drop size on forced trials was not included in this calculation.

*Initial training.* On the first day of training, the ITI was 10 s and the standard was 100  $\mu$ L of water presented immediately. The rats were trained in daily 1-hr sessions under these conditions until they completed 60 trials within a 1-hr period. The rats learned to make the center snout-poke response and choose between the left and right water dispensers in 2 to 5 days. Then the ITI was set at 30 s, and the regular experimental procedure was implemented. No further shaping by the experimenter was required.

*Experimental sessions.* After initial training, the experiment continued for 15 weeks with delays of 0, 2, 4, 8, and 16 s. The data from the last 5 weeks of this period were analyzed.

### Results and Discussion

*Adjustment across trials within a session.* The top left of Figure 2 shows the average imme-

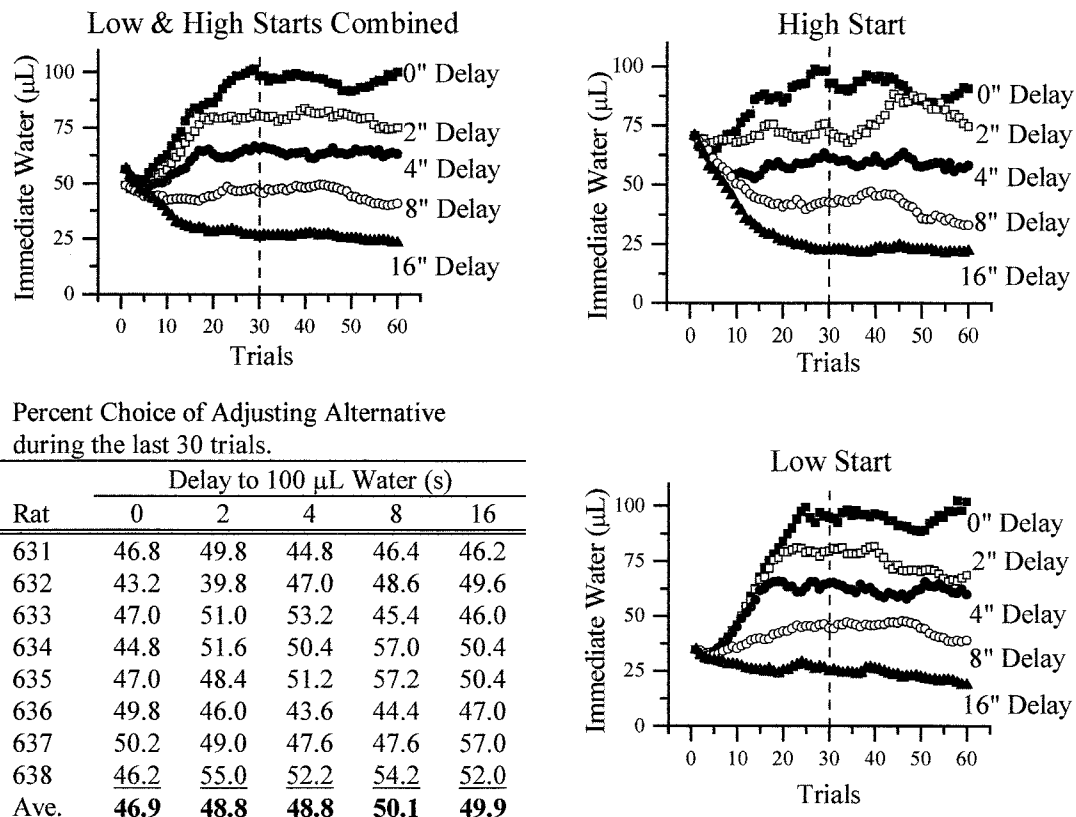


Fig. 2. Adjustment across trials of the amount of immediate water when tested with different delays in Experiment 1. The dashed line indicates 30 trials.

diate drop size delivered from the adjusting alternative for 8 rats within each session over the 5-week period. This plot is averaged across high and low starting amounts on the adjusting side (see Table 1). The top and bottom right plots of Figure 2 show the average adjusted amount of water for the 8 rats when the adjusted amount started at high (71  $\mu$ l) and low (35  $\mu$ l) immediate amounts, respectively. The flat portions of the five traces in these plots (each indicating a different delay) indicate that the rats chose the delayed 100- $\mu$ l amount of water and the adjusted amount with equal frequency. Inspection of the plots for high and low starting amounts in Figure 2 shows that the amount of immediate water was rapidly adjusted toward the indifference point as a function of delay. For example, in the 4-s delay condition, the high starting amount resulted in an initial decrease in immediate amount, and the low starting amount resulted in an initial increase in immediate amount. Figure 2 shows that the rats reached the indifference point within the first 30 trials at all delays, and these indifference points were not affected by different starting amounts on the adjusting side. The table in Figure 2 shows the percentage of choices of the adjusting alternative during the last 30 trials of the session for the individual rats (high and low starts combined). A value of 50% indicates that the rats chose the standard and adjusting alternative with equal frequency. Inspection of the table shows that all of the rats had choice alternatives close to 50%.

As expected, when the standard was 100  $\mu$ l of water presented with no delay, the rats adjusted the amount of immediate water to approximately 100  $\mu$ l. With longer delays, the animals adjusted the amount of immediate water in direct relation to the duration of the delay. For example, the value of 100  $\mu$ l of water delayed by 16 s was approximately the same as 25  $\mu$ l presented immediately. These data also indicate that the rats adapted within a single session to delay conditions that changed daily. Individual-subject plots of the averaged group data depicted in Figure 2 show the same clear differences between delay values but with more variability from trial to trial.

*Hyperbolic discount functions.* Discount functions for the 8 individual rats as well as for

the group average were determined. Figure 3 shows that both the group-average and individual-animal data were well described by the hyperbolic discount function (Equation 1). The coefficients of determination ranged from 0.83 to 0.99 (see Figure 3). There was individual variability in the steepness of the discount functions. The values of  $k$  ranged from 0.36 to 0.07 (see Figure 3), where larger values denote more rapid discounting. The value of  $b$  describes a bias for either the standard ( $b > 1.0$ ) or the adjusting alternative ( $b < 1.0$ ). Five of the rats had  $b$  values less than 1.0, whereas the other 3 rats had  $b$  values greater than 1.0. The cause of bias in individual animals and its interpretation are unclear. However it is important to take into account because some rats showed large biases (see Rats 631 and 638 in Figure 3).

*No contrast effects caused by varying delay daily.* The adjusting-amount procedure involves testing a different standard (delay) every day. Changing the standard daily has the advantage of permitting a rapid determination of the discount curves shown in Figure 3. A rapid determination of discount curves also has the practical advantage of permitting a more efficient method of determining the effects of drugs and other manipulations on the shape of the discount function.

A potential problem with this procedure is that there may be contrast effects due to the order in which the delay values are tested. For example, testing a delay of 16 s on the day following a 0-s delay might have a different result from testing a delay of 16 s following an 8-s delay. During the 5-week period in which the data for Figure 3 were collected, each delay was preceded by the other four delays at least once. Table 2 shows the indifference points collected at each of the five delays during this period as a function of the delay tested on the previous day. An order effect would be indicated by a systematic change in the indifference points as a function of the test delay on the preceding day. The data in Table 2 show that there was no effect of order on testing.

The data collected in Experiment 1 indicate that the adjusting-amount procedure, used in conjunction with daily changes in the standard, can be used to rapidly determine discount functions for delay. At present, there is no evidence that a similar type of 1-day pro-

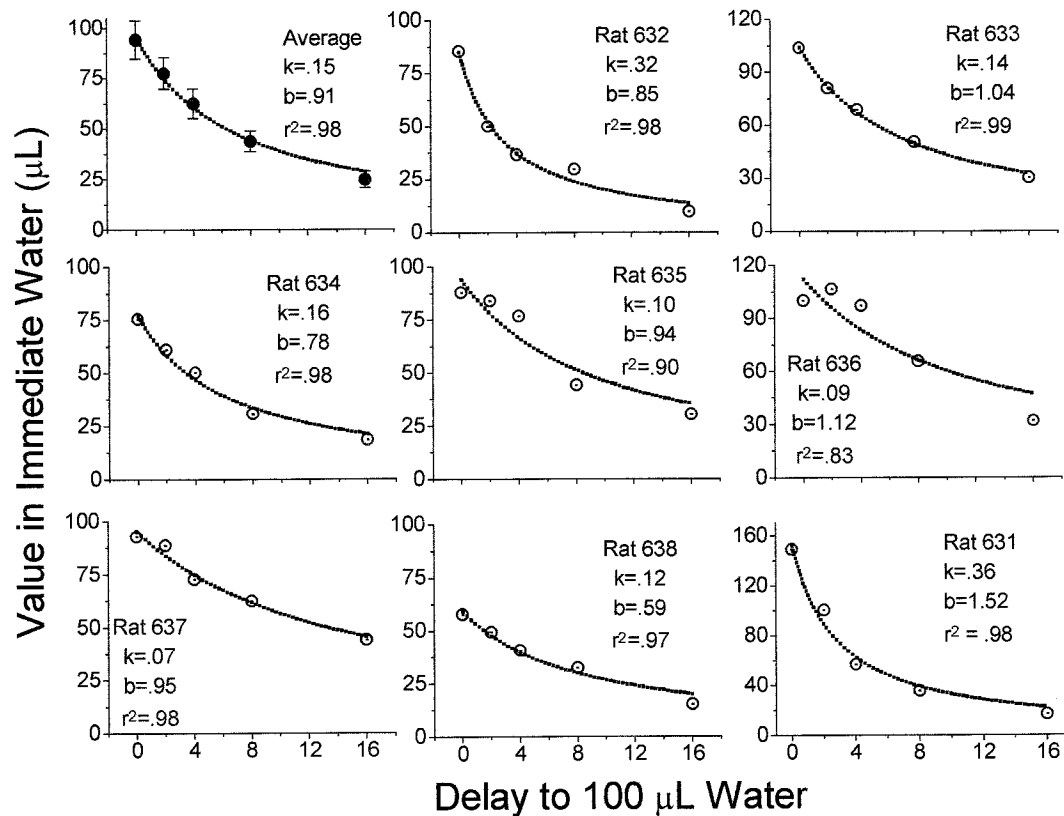


Fig. 3. The average and individual-subject discount curves for Experiment 1. The adjusted microliters of water is plotted as a function of the standard delay for 100 μL of water. The dashed line indicates the best fitting hyperbolic discount function.

cedure could not be used with adjusting delays instead of adjusting amounts. The following experiments use the adjusting-amount procedure to examine the effects of deprivation level and the magnitude of the standard on the discount function.

## EXPERIMENT 2

Previous research examining the effects of deprivation level on choice between delayed and immediate reinforcers has produced conflicting results. Some researchers have re-

Table 2  
Mean indifference points for 8 rats organized according to delay value on the test and the preceding training day in Experiment 1.

Delay value on preced- ing day (s)	Delay value on test day (s)				
	0	2	4	8	16
0		80.0 ± 8.4	61.4 ± 8.6	42.6 ± 5.8	26.8 ± 4.9
2	92.2 ± 6.5		63.7 ± 9.6	49.0 ± 6.5	19.9 ± 5.2
4	103.6 ± 22.2	73.9 ± 9.2		43.7 ± 4.9	24.8 ± 4.7
8	84.9 ± 8.2	76.7 ± 6.8	66.8 ± 9.3		28.7 ± 4.4
16	94.9 ± 7.3	74.0 ± 8.6	55.5 ± 7.7	36.0 ± 6.1	

Note. The values are the mean ± SEM.

Table 3

Response latencies during the baseline, partial satiation, and rebaseline phases at each of the delay values in Experiment 2.

Delay to reinforcer	Response latency (s)		
	Baseline	Satiation	Rebaseline
0	0.90 $\pm$ 0.06	1.78 $\pm$ 0.57	0.96 $\pm$ 0.04
2	0.99 $\pm$ 0.07	2.33 $\pm$ 0.88	1.04 $\pm$ 0.43
4	1.51 $\pm$ 0.41	4.84 $\pm$ 3.11	1.07 $\pm$ 0.07
8	3.65 $\pm$ 2.37	10.54 $\pm$ 4.86	1.37 $\pm$ 0.12
16	4.04 $\pm$ 2.41	8.78 $\pm$ 2.45	3.31 $\pm$ 1.07

*Note.* The values are the mean  $\pm$  SEM. Response latencies indicate the mean amount of time taken by the rats to make the center snout-poke response after trial onset. Trial onset was signaled by turning on the center stimulus light.

ported that increased deprivation can increase preference for large delayed reinforcers (Bradshaw & Szabadi, 1992; Christensen-Szalanski, Goldberg, Anderson, & Mitchell, 1980). Other researchers have reported that increased levels of deprivation are associated with decreased preference for large delayed reinforcers (Eisenberger & Masterson, 1987; Snyderman, 1987). Still other researchers have reported no effect on preference (Logue, Chavarro, Rachlin, & Reeder, 1988; Logue & Peña-Correal, 1985). The current study was conducted to determine the effects of water deprivation level on discounting.

#### Method

*Subjects and apparatus.* The same subjects and apparatus were used as described for Experiment 1.

*Procedure.* Following the 5 weeks of Experiment 1, the rats were given an additional 20 min of water 4 hr prior to the session as well as the usual 20-min access to water immediately after the session. This partial satiation period lasted for 8 weeks. Performance on the task for the last 4 weeks of the partial satiation period was used to determine the effects of changing deprivation level. After the 8-week partial satiation period, the rats were returned to the treatment that provided only 20-min access to water immediately after the session. The first 4 weeks of the baseline recovery period were used to determine the effects of reinstating the previous level of water deprivation.

Table 4

Choice latencies during the baseline, partial satiation, and rebaseline phases at each of the delay values in Experiment 2.

Delay to reinforcer	Choice latency (s)		
	Baseline	Satiation	Rebaseline
0	0.65 $\pm$ 0.12	0.69 $\pm$ 0.07	0.66 $\pm$ 0.09
2	0.65 $\pm$ 0.09	0.74 $\pm$ 0.09	0.66 $\pm$ 0.08
4	0.67 $\pm$ 0.08	0.72 $\pm$ 0.07	0.65 $\pm$ 0.06
8	0.65 $\pm$ 0.07	0.80 $\pm$ 0.07	0.67 $\pm$ 0.07
16	0.72 $\pm$ 0.09	0.97 $\pm$ 0.16	0.73 $\pm$ 0.10

*Note.* The values are the mean  $\pm$  SEM. Choice latency indicates the mean time taken by the 8 rats to move from the center snout-poke hole and respond on the test standard or adjusting alternative.

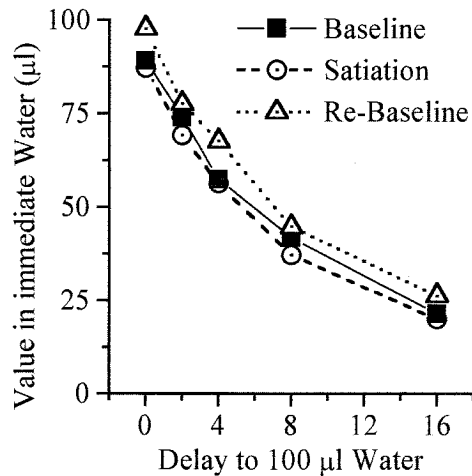
#### Results and Discussion

Increased access to water resulted in increased body weight. At the beginning of the partial satiation period, the average weight of the rats immediately before testing was  $416 \pm 8$  g ( $M \pm SEM$ ). During the last 4 weeks of the partial satiation period, the average weight of the rats immediately before testing was  $469 \pm 7$  g. After the partial satiation period, the average weight of the rats during the baseline recovery period was  $440 \pm 9$  g.

Decreasing deprivation level increased response latency (Table 3). The response latency was the time it took a rat to make a snout-poke response after the center stimulus light that signaled trial onset was turned on. The data in Table 3 were analyzed using a two-factor within-subject analysis of variance (ANOVA) with repeated measures on deprivation level (three) and delay (five). There were significant main effects of both partial satiation,  $F(2, 14) = 5.30$ ,  $p < .05$ , and delay,  $F(4, 28) = 12.23$ ,  $p < .0001$ . The interaction was not significant,  $F(8, 56) = 1.57$ ,  $p > .05$ . These results indicate that decreasing deprivation level and increasing delay systematically increased the response latencies.

Decreasing deprivation level also significantly increased choice latency (Table 4). The choice latency was the time it took a rat to move from the center snout-poke hole and choose either the standard or the adjusting alternative. The data in Table 4 were analyzed in the same way as those for response latencies: a two-way ANOVA with repeated measures on deprivation level (three) and delay





Values of  $k$ ,  $b$ , and  $r^2$  for the individual rats during Baseline, Satiation and Re-Baseline phases of water deprivation experiment..

Rat	Baseline			Satiation			Re-Baseline		
	$k$	$b$	$r^2$	$k$	$b$	$r^2$	$k$	$b$	$r^2$
631	.36	1.52	.98	.07	1.09	.76	.09	1.10	.99
632	.32	0.85	.98	.37	0.96	.99	.25	0.91	.99
633	.14	1.04	.99	.09	0.88	.94	.21	1.21	.98
634	.16	0.78	.98	.29	0.77	.98	.13	0.75	.94
635	.10	0.74	.90	.26	0.82	.93	.18	1.12	.99
636	.09	1.12	.83	.06	0.94	.95	.05	1.15	.82
637	.07	0.95	.98	.08	1.11	.90	.09	1.04	.99
638	.12	0.59	.97	.31	0.84	.99	.32	1.04	.99
<b>Ave.</b>	<b>.15</b>	<b>0.91</b>	<b>.98</b>	<b>.17</b>	<b>0.89</b>	<b>.99</b>	<b>.14</b>	<b>.99</b>	<b>.99</b>

Fig. 4. The  $k$  values of the best fitting hyperbolic discount functions indicated that increasing access to water did not effect discounting of reinforcer value by delay in Experiment 2. The table indicates the  $r^2$  and best fitting values of  $k$  and  $b$  for the individual rats. The Ave row of the table (in bold) indicates the best fitting  $k$  and  $b$  values for the average indifference points shown in the plot. The indifference points for the individual animals are provided in Appendix A.

(five). There were main effects of deprivation level,  $F(2, 14) = 13.53$ ,  $p < .001$ , and delay on choice latency,  $F(4, 28) = 3.77$ ,  $p < .05$ . The interaction was not significant,  $F(8, 56) = 1.95$ ,  $p > .05$ . These data indicate that increasing both satiation and delay systematically increased the choice latencies.

Figure 4 shows that partial satiation did not affect the rate of discounting of reinforcer value by delay. (Indifference points for individual animals are presented in Appendix A.) There were no significant changes in the value of  $k$  or  $b$  associated with changing levels of water deprivation. These results indicate that decreasing the level of water deprivation did not affect discounting by delay. The observed increases in body weight and increases in the response and choice latencies indicate that the levels of partial satiation used in this experiment were sufficient to produce physiological and behavioral changes. These results indicate that speed of responding (indicated by response and choice latencies) and discounting can change independently.

As noted in the Introduction, some researchers have found that decreasing deprivation level causes an increase in preference for the delayed reinforcer (Bradshaw & Szabadi, 1992; Christensen-Szalanski et al.,

1980), whereas others have found that decreasing deprivation level causes an increase in preference for the immediate reinforcer (Eisenberger & Masterson, 1987; Snyderman, 1987). However, the present results are consistent with those of Logue and her colleagues (Logue et al., 1988; Logue & Peña-Correal, 1985), who also reported no effect of deprivation level on choice between delayed and immediate reinforcers. Logue and Peña-Correal (1985) also found that decreasing deprivation level increased the latency of pigeons to eat from the food hopper. Logue (1988) suggested that one way to interpret these results is that deprivation level affects the value of both the immediate and delayed reinforcers proportionally so that there was no change in the relative values of the delayed and immediate reinforcers.

An interesting result of this experiment is that the speed of responding (response and choice latencies) became slower as delay to the reinforcer was increased. This effect was independent of satiation, because it occurred during both the baseline phases of the experiment and in the satiation phase. The rats responded just as fast (or slowly) when choosing the immediate adjusting alternative as when they chose the delayed standard alter-

native. This pattern of results is consistent with the interpretation that response and choice latencies reflect the discounted value of the delayed reinforcer. Presumably, the rats responded more slowly to the delayed 100- $\mu$ l standard because its value was discounted. Similarly, the rats responded more slowly to the immediate adjusting alternative because the smaller amounts of water produced by this choice reflected the discounted value of the delayed 100- $\mu$ l standard.

### EXPERIMENT 3

In humans, the rate of discounting has been shown to be related to the size of the standard. That is, the value of a smaller standard amount decreases more rapidly with increasing delay than does the value of a larger standard amount (Green *et al.*, 1994; Kirby & Marakovic, 1996; Myerson & Green, 1995; Raineri & Rachlin, 1993). For example, Green *et al.* showed that humans discounted the value of a hypothetical \$1,000 reinforcer more rapidly than a hypothetical \$10,000 reinforcer. In the present experiment we examined whether discounting varies with the amount of delayed water available as the standard. The rats were tested with three different standard amounts (100, 150, and 200  $\mu$ l) presented in combination with five different delays (0, 2, 4, 8, and 16 s).

#### Method

*Subjects and apparatus.* The same subjects and apparatus as described in Experiment 1 were used. The data from only 7 rats are presented because one of the original rats developed a tumor during the experiment.

*Procedure.* At the end of the 4-week baseline recovery period described in Experiment 2, we began to vary the amount of water as well as the delay to water delivery associated with the standard reinforcer. Three different amounts of water (100, 150, and 200  $\mu$ l) and five different delays (0, 2, 4, 8, and 16 s) were combined, creating a total of 15 different standards to be examined. The three amounts were varied so that each amount was combined with each of the five delays during a 3-week period in a pseudorandom order. The rats were tested under these conditions for 15 weeks. The last 12 weeks were analyzed.

#### Results and Discussion

The rats readily adapted to the three different reinforcer amounts (Figure 5, top). This is particularly clear at the 0-s delay value, where the adjusted amounts approximately matched the amounts of the standards. Orderly discount functions were obtained for the three different amounts of water (Figure 5). The  $k$  values tended to increase as the amount of reinforcement increased, indicating that the rate of discounting increased as a function of amount. The data were also plotted as a proportion of the three standard amounts (Figure 5, bottom). When viewed in this manner, the differences in the three discounting curves appear to be small. The  $k$  values for the individual animals were subjected to statistical analysis using a one-factor within-subject ANOVA. The increase in the value of  $k$  as a function of amount fell just short of statistical significance,  $F(2, 12) = 3.08$ ,  $p = .08$ . Indifference points for individual animals are presented in Appendix B.

Data from studies with humans indicate that small amounts of money are discounted more rapidly than large amounts of money (Green *et al.*, 1994; Kirby & Marakovic, 1996; Myerson & Green, 1995; Raineri & Rachlin, 1993). In the present study, rats did not discount small amounts of water more rapidly than large amounts of water, and, in fact, tended to discount small amounts *less* rapidly than large amounts. There are many potential explanations for the different results. In most of the studies with humans, the amounts and delays were hypothetical. Using real rewards, Kirby and Marakovic (1995) reported no effect of reinforcer amount on discounting. However, in another study, subjects who received real reinforcers discounted small amounts of money more than large amounts of money (Kirby & Marakovic, 1996). In both cases (hypothetical and real), the volunteers did not make choices based on previous experience with receiving delayed money within the context of the experimental situation. In contrast, the rats in the present study made their choices based on experience with receiving delayed water during the experimental situation. When the subject has experience with receiving reinforcers in the experimental situation, value discounting may be influenced not only by the amount of

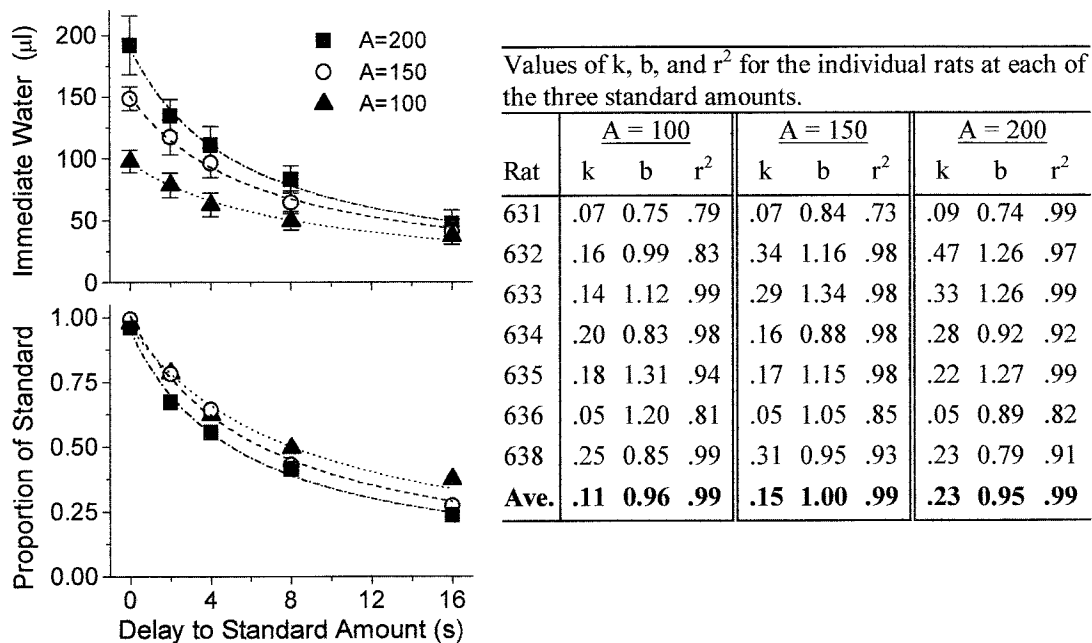


Fig. 5. The data depicted in the top graph show discounting by delay of the value of three different standard amounts (100, 150, and 200  $\mu$ l) in Experiment 3. The data depicted in the bottom graph are normalized by dividing the immediate value (in microliters) at each delay by the standard amounts of 100, 150, and 200  $\mu$ l. The table indicates the  $r^2$  and best fitting values of  $k$  and  $b$  for the individual rats. The indifference points for the individual animals are provided in Appendix B.

the reinforcer earned after each individual choice but also by the cumulative amount of reinforcer earned during the experimental session. Thus, the choices of the rats in the present experiment may have been influenced not only by the amount of water earned after each individual choice but also by the cumulative amount of water earned during the experimental session. More rapid discounting of value would lead to less cumulative water intake at the end of the session. When the standard amount is small, smaller cumulative amounts of the reinforcer are earned, and the subject may be more sensitive to reductions in the cumulative amount of the reinforcer earned because of discounting. In contrast, when the standard amounts are large, larger cumulative amounts of the reinforcer are available, and the subject may be less sensitive to reduction of cumulative amount of reinforcer earned because of discounting. It may be that actual experience of reinforcers and delays is an important determinant of discounting.

Another explanation could be that there was a floor effect; that is, an asymptotic min-

imum reinforcer value for a given amount, no matter what the length of the delay. A floor effect could have prevented the 100- $\mu$ l standard amount from being discounted more steeply than the 200- $\mu$ l standard amount. Using human subjects, Kirby and Marakovic (1995) also failed to obtain increased discounting with smaller reinforcers, and suggested that this was because the amounts of money they used as standard amounts were too small. There are many other methodological differences between the previous studies with humans and the present study (e.g., money vs. water as reinforcers, the time scale, and the species), making it impossible to identify the reason for the discrepancy. However, the present results indicate that small reinforcers are not always discounted more rapidly than large reinforcers.

This experiment demonstrated that rats are capable of adjusting to 15 different conditions that were changed daily. This flexibility indicates that the adjusting-amount procedure is sensitive to day-to-day changes in reinforcer value. This point may be particularly important for testing the effects of drugs

and other acute treatments. Charrier and Thiebot (1996) recently reported that acute (single-session) changes in delay and amount did not affect choice behavior in rats trained to choose between a large five-pellet reinforcer given after a long 30-s delay and a small one-pellet reinforcer given after a short 5-s delay. These authors concluded that their operant paradigm was not sensitive to acute changes and therefore would not be useful to evaluate the effects of acute treatments such as drugs. In contrast, the results of the present experiments indicate that the adjusting-amount procedure is sensitive to acute treatments.

### GENERAL DISCUSSION

The data collected in Experiments 1, 2, and 3 indicated that the adjusting-amount procedure, used in conjunction with daily changes in the standard, can be used to rapidly determine discount functions for delay. The studies showed that stable hyperbolic discount functions could be obtained under a variety of experimental conditions, including satiation and changing the standard amounts. Whether a similar 1-day procedure could be used in conjunction with adjusting delays instead of adjusting amounts has yet to be determined. Two unexplored aspects of the adjusting-amount procedure that may influence the results are the use of forced trials and the use of a 10% step size for the adjusting alternative. The purpose of the forced trials was to insure that the subjects experienced both alternatives. It is not clear from the present results what, if any, effects forced trials had on the obtained results. The 10% adjustment was used because many perceptual judgments are known to be better described by logarithmic or power functions than by linear functions (Stevens, 1975). One possible disadvantage of the 10% adjustment procedure is that it may produce a floor effect because the adjustments may become so small as the amount decreases that the animal fails to reach an indifference point within the allotted 60 trials. However, this did not occur in the present experiments: Figure 2 shows that the choice ratios were close to 50% during the last 30 trials at the longest (16-s) delay, indicating indifference between the two alternatives.

There are two potential problems related to inferring discount functions from data generated by the adjusting-amount procedure. First, in finding the best fitting hyperbolic function (i.e., Equation 1) to the data, we made the assumption that  $A$  is linearly related to the amount of water. In other words, we are making the assumption that 200  $\mu\text{l}$  is exactly twice as valuable as 100  $\mu\text{l}$ . This may not be true. It is possible to design experiments that would address this issue directly. For now, we argue that the adjusting-amount procedure produces at least a rough estimate of reinforcer value. The exact relationship between reinforcer value and amount will need to be addressed in future experiments.

Second, when interpreting the results from the adjusting-amount task, we assume that the rat chooses the alternative that has the greatest reinforcing value on each trial. However, consideration of the adjusting-amount task reveals that the rats could learn to maximize the overall amount of water available during the test session by repeatedly choosing the test standard in order to drive the amount of the adjusting reinforcer up and then switching between the test standard and adjusting alternative for the rest of the session. If the rats did this, the amount of water on the adjusting side would not reflect the reinforcing value of the standard. However, the results show that the rats did not learn to optimize water intake in this way. Experiment 3 showed that when the test standard was set at 100, 150, and 200  $\mu\text{l}$  presented with no delay, the rats matched these values on the adjusting side. They did not drive the adjusting alternative above the value of the standard, as would be predicted if they had learned to maximize the overall water amount.

In future studies, the adjusting-amount procedure can be used to determine indifference points for a variety of different kinds of consequences. For example, the standard could be an immediate quantity of water presented with a probability of less than 1.0 while the adjusting alternative is a varying quantity of water presented at a probability of 1.0. We would expect that the indifference point would decrease as the probability of water decreased. Alternatively, the standard could be immediate water paired with a punishing stimulus such as electric shock. In this case, we would expect that the indifference point

would decrease as the intensity of the shock associated with the standard was increased. A variety of different consequences could be evaluated using the adjusting-amount procedure with only the nature of the standard being varied. The value of the standard is always measured in terms of equivalent immediate microliters of water on the adjusting side. Thus equivalent immediate microliters of water serves as a common currency to measure the value of the standards across experiments. The concept of a common currency is important because it permits a direct comparison across different kinds of consequences.

A number of authors (Ainslie, 1975; Herrnstein, 1981; Logue, 1988; Rachlin, 1995) have proposed a discounting model of impulsive behavior. According to this model, the value of future consequences is discounted more rapidly as a function of delay for impulsive individuals than for nonimpulsive individuals. Consequently, impulsive individuals make decisions that do not adequately weigh future (delayed) consequences. The present data indicate that the adjusting-amount procedure may be an effective way to measure how rapidly the value of reinforcers diminishes with delay for different individuals. Thus, the adjusting-amount procedure may provide a useful laboratory model of impulsive behavior. The basic metric of this model is the value of  $k$  in Mazur's hyperbolic discount function. Large values of  $k$  indicate steeper discounting and greater impulsivity.

In summary, the experiments presented in this paper indicate that the adjusting-amount procedure is a useful way to measure discounting by delay. The rats adjusted to daily changes in both delay and amount so that discount functions could be rapidly determined. The results obtained with the adjusting-amount procedure were consistent with those previously reported by Mazur (1987) using an adjusting-delay procedure. The obtained discount functions were hyperbolic, and their steepness could be quantitatively described using the value of  $k$  in Mazur's hyperbolic discount function.

## REFERENCES

- Ainslie, G. (1975). Specious reward: A behavioral theory of impulsiveness and impulse control. *Psychological Bulletin*, 82, 463-496.
- Bradshaw, C. M., & Szabadi, E. (1992). Choice between delayed reinforcers in a discrete-trials schedule: The effect of deprivation level. *Quarterly Journal of Experimental Psychology*, 44B, 1-16.
- Charrier, D., & Thiebot, M. H. (1996). Effects of psychotropic drugs on rat responding in an operant paradigm involving choice between delayed reinforcers. *Pharmacology Biochemistry and Behavior*, 54, 149-157.
- Christensen-Szalanski, J. J., Goldberg, A. D., Anderson, M. E., & Mitchell, T. R. (1980). Deprivation, delay of reinforcement, and the selection of behavioral strategies. *Animal Behaviour*, 28, 341-346.
- Eisenberger, R., & Masterson, F. A. (1987). Effects of prior learning and current motivation on self-control. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analysis of behavior: Vol. 5. The effect of delay and intervening events on reinforcement value* (pp. 267-282). Hillsdale, NJ: Erlbaum.
- Green, L., Fry, A., & Myerson, J. (1994). Discounting of delayed rewards: A life-span comparison. *Psychological Science*, 5, 33-36.
- Herrnstein, R. J. (1981). Self-control as response strength. In C. M. Bradshaw, E. Szabadi, & C. F. Lowe (Eds.), *Quantification of steady-state operant behavior* (pp. 3-20). Amsterdam: Elsevier.
- Kirby, K. N., & Marakovic, N. N. (1995). Modeling myopic decisions: Evidence for hyperbolic delay-discounting within subjects and amounts. *Organizational Behavior and Human Decision Processes*, 64, 22-30.
- Kirby, K. N., & Marakovic, N. N. (1996). Delay-discounting probabilistic rewards: Rates decrease as amounts increase. *Psychonomic Bulletin & Review*, 3, 100-104.
- Logue, A. W. (1988). Research on self-control: An integrated framework. *Behavioral and Brain Sciences*, 11, 665-709.
- Logue, A. W., Chavarro, A., Rachlin, H., & Reeder, R. W. (1988). Impulsiveness in pigeons living in the experimental chamber. *Animal Learning & Behavior*, 16, 31-39.
- Logue, A. W., & Peña-Correal, T. E. (1985). The effect of food deprivation on self-control. *Behavioral Processes*, 10, 355-368.
- Mazur, J. E. (1987). An adjusting procedure for studying delayed reinforcement. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analysis of behavior: Vol. 5. The effect of delay and intervening events on reinforcement value* (pp. 55-73). Hillsdale, NJ: Erlbaum.
- Mazur, J. E. (1989). Theories of probabilistic reinforcement. *Journal of the Experimental Analysis of Behavior*, 51, 87-99.
- Mazur, J. E. (1991). Choice with probabilistic reinforcement: Effects of delay and conditioned reinforcers. *Journal of the Experimental Analysis of Behavior*, 55, 63-77.
- Mazur, J. E. (1995). Conditioned reinforcement and choice with delayed and uncertain primary reinforcers. *Journal of the Experimental Analysis of Behavior*, 63, 139-150.
- Myerson, J., & Green, L. (1995). Discounting of delayed rewards: Models of individual choice. *Journal of the Experimental Analysis of Behavior*, 64, 263-276.
- Rachlin, H. (1995). Self-control: Beyond commitment. *Behavioral and Brain Sciences*, 18, 109-159.
- Rachlin, H., Raineri, A., & Cross, D. (1991). Subjective

- probability and delay. *Journal of the Experimental Analysis of Behavior*, 55, 233–244.
- Raineri, A., & Rachlin, H. (1993). The effect of temporal constraints on the value of money and other commodities. *Journal of Behavioral Decision Making*, 6, 77–94.
- Snyderman, M. (1987). Prey selection and self-control. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analysis of behavior: Vol. 5. The effect of delay and intervening events on reinforcement value* (pp. 283–308). Hillsdale, NJ: Erlbaum.
- Stevens, S. S. (1975). *Psychophysics*. New York: Wiley.

*Received October 4, 1996*

*Final acceptance January 28, 1997*

## APPENDIX A

Indifference points obtained for the individual rats in Experiment 2. The indifference points are in microliters of water.

Rat	Baseline					Satiation					Rebaseline				
	0	2	4	8	16	0	2	4	8	16	0	2	4	8	16
631	153	103	58	37	17	97	118	82	65	47	111	95	83	66	46
632	86	51	58	37	17	95	64	44	23	14	92	59	46	34	16
633	105	81	68	51	31	87	74	70	57	29	119	88	72	40	24
634	76	61	51	32	19	79	43	38	26	13	72	62	57	35	18
635	90	87	77	44	30	82	52	52	21	8	112	83	72	43	26
636	98	110	96	66	32	90	91	79	65	46	105	117	100	89	55
637	93	88	73	65	47	109	105	81	58	57	106	88	79	58	47
638	56	50	42	32	15	84	53	37	24	15	105	60	50	30	15

## APPENDIX B

Indifference points obtained for the individual rats in Experiment 3. The indifference points are in microliters of water.

Rat	Amount = 100					Amount = 150					Amount = 200				
	0	2	4	8	16	0	2	4	8	16	0	2	4	8	16
631	81	63	48	56	38	137	91	89	100	53	149	128	109	84	61
632	104	62	76	35	36	173	113	61	48	34	256	112	89	78	34
633	112	90	72	52	35	203	120	102	53	45	256	136	114	76	45
634	82	63	50	27	19	132	99	81	50	44	184	128	61	74	38
635	135	94	71	50	49	171	131	111	60	47	251	180	136	91	45
636	116	118	91	100	58	147	155	132	126	76	171	183	145	110	107
638	87	53	43	33	16	147	75	62	46	41	150	137	71	50	24