

*CHOICE BETWEEN DELAYED REINFORCERS AND
FIXED-RATIO SCHEDULES REQUIRING
FORCEFUL RESPONDING*

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This experiment measured pigeons' choices between delayed reinforcers and fixed-ratio schedules in which a force of approximately 0.48 N was needed to operate the response key. In ratio-delay conditions, subjects chose between a fixed-ratio schedule and an adjusting delay. The delay was increased or decreased several times a session in order to estimate an indifference point—a delay duration at which the two alternatives were chosen about equally often. Each ratio-delay condition was followed by a delay-delay condition in which subjects chose between the adjusting delay and a variable-time schedule, with the components of this schedule selected to match the ratio completion times of the preceding ratio-delay condition. The adjusting delays at the indifference point were longer when the alternative was a fixed-ratio schedule than when it was a matched variable-time schedule, which indicated a preference for the matched variable-time schedules over the fixed-ratio schedules. This preference increased in a nonlinear manner with increasing ratio size. This nonlinearity was inconsistent with a theory that states that indifference points for both time and ratio schedules can be predicted by multiplying the choice response-reinforcer intervals of the two types of schedules by different multiplicative constants. Two other theories, which predict nonlinear increases in preference for the matched variable-time schedules, are discussed.

Key words: fixed ratio, variable time, response effort, reinforcer delay, adjusting procedure, key peck, pigeons

A number of recent experiments have suggested that the relation between a reinforcer's delay and its value (its ability to sustain instrumental responding) can be described by a hyperbolic equation (e.g., Davison & Smith, 1986; Mazur, 1984, 1986, 1987; Mazur, Stellar, & Waraczynski, 1987). In his experiments, Mazur has used an adjusting-delay procedure, which involves a series of discrete trials on which subjects choose between a *standard alternative*, for which the delay to reinforcement is constant within a condition, and an *adjusting alternative*, for which the delay repeatedly changes depending on a subject's previous choices. The purpose of these adjustments is to estimate an *indifference point*—a delay at which the two alternatives are chosen equally often. By varying the standard delay across conditions and obtaining a number of indifference-point estimates, inferences about the relation between reinforcer delay and value can be made.

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In one experiment with pigeons (Mazur, 1987), the reinforcer duration was 2 s for the standard alternative and 6 s for the adjusting alternative. By varying the delay for the 2-s reinforcer across conditions, a series of indifference points was obtained, each point representing a pair of delay-amount combinations with equal value. Mazur showed that the results were consistent with the following hyperbolic equation:

$$V_i = \frac{A_i}{1 + K_i D_i}, \quad (1)$$

where V_i is the value of alternative i , A_i is monotonically related to the amount of reinforcement, D_i is the delay between a choice response and reinforcement, and K_i is a free parameter. K_i is subscripted here because this parameter may vary depending on what events take place during the delay, as discussed below. Assuming that $V_s = V_a$ at the indifference point (where the subscripts represent the standard and adjusting alternatives, respectively), it follows from Equation 1 that

$$D_a = \frac{A_a - A_s}{K_s A_s} + \frac{A_a}{A_s} D_s. \quad (2)$$

If A_a is greater than A_r , as was the case in the Mazur (1987) experiment, Equation 2 predicts that when D_a is plotted as a function of D_r , the resultant indifference function should be linear, with a y intercept greater than zero and a slope greater than one. The results from each of the 4 pigeons in Mazur's experiment supported this prediction, as did the results from a similar study with rats as subjects and electrical stimulation of the brain as the reinforcer (Mazur et al., 1987). Mazur (1987) showed that indifference functions of this form are inconsistent with a number of other equations relating delay and value, including the exponential ($V_i = A_i \cdot \exp[-KD_i]$) and a simple reciprocal relation ($V_i = A_i/KD_i$).

Grossbard and Mazur (1986) conducted a similar experiment with pigeons, except that the fixed and adjusting delays of the above studies were replaced with fixed-ratio (FR) and adjusting-ratio schedules. They plotted indifference functions by using the mean times to complete the standard and adjusting ratios as measures of D_r and D_a , respectively. These functions were also approximately linear, with y intercepts greater than zero and slopes greater than one. Grossbard and Mazur therefore suggested that Equation 1 may describe the relation between delay and value both when a response requirement must be satisfied during the delay and when no responses are required. This does not imply, however, that animals are indifferent between delay intervals in which no responses are required and those in which a response requirement must be met. In other conditions, Grossbard and Mazur used a fixed delay, or a fixed-time (FT) schedule, as the standard alternative and a ratio schedule as the adjusting alternative. By comparing these indifference points with those from the ratio-ratio choices, Grossbard and Mazur found that 3 of 4 subjects showed a preference for FT schedules over FR schedules that had the same average times between a choice response and reinforcement. Other studies have found similar effects of the presence versus absence of a ratio requirement on choice responses (Mazur, 1986) and on preratio pauses (Crossman, Heaps, Nunes, & Alferink, 1974).

The aforementioned studies suggest (a) that a hyperbolic equation describes the relation between delay and value for both delay-delay choices and ratio-ratio choices, and (b) that animals show a preference for simple delays

in delay-ratio choices. How can these two findings be reconciled within a single equation for reinforcer delay? As one possibility, Mazur (1986) suggested that the parameter K_i , which determines how rapidly V_i decreases as D_i increases, might assume a larger value with ratio schedules than with time schedules. (That is, K_i would be some positive number for a time schedule and a larger number for a ratio schedule. The exact values of K_i could be expected to vary across subjects.) The value of K_i might be larger because of the effort involved in making the instrumental responses. A larger value of K_i could also be viewed as reflecting the greater aversiveness of a response requirement as compared to a simple delay. To see the implications of two different values of K_i , consider a choice situation in which the standard alternative is an FT schedule, the adjusting alternative is a ratio schedule, and the two reinforcer amounts are equal. If K_r and K_d represent the decay parameters for the ratio and time schedules, respectively, then Equation 1 predicts that at the indifference point,

$$D_r = \frac{K_d}{K_r} D_d. \quad (3)$$

Because in this situation D_r represents the mean time to complete the ratio requirement, Equation 3 predicts that if $K_r > K_d$, ratio completion times will be shorter than FT durations by a constant proportion. Mazur's (1986) study included four delay-ratio conditions, and the obtained indifference points were roughly consistent with Equation 3, although there was a fair amount of variability in the data.

Although the results of Mazur (1986) and Grossbard and Mazur (1986) were both at least approximately consistent with the hypothesis that K_i is greater with ratio schedules than with time schedules, two features of these studies limit their informativeness. First, in both studies, the force required to operate the response keys was minimal (0.10 N). This force requirement is typical for studies involving key pecking by pigeons, but if one is interested in how the presence or absence of a response requirement affects preference, requiring a more effortful response might well provide a clearer answer. In the present studies, the key associated with an FR schedule required 0.48 N to operate. The second prob-

lem with the previous studies was that the time subjects took to complete a given ratio requirement varied from one trial to the next, so the choice was actually between a fixed delay with no response requirement and a variable delay with required responses. Because animals are known to choose variable over fixed delays if their mean times to reinforcement are equal (e.g., Mazur, 1984; Rider, 1983), preference for the FT schedules may have been lessened because of the variability in the ratio completion times.

The present experiment was designed to control for the variability in ratio completion times. In ratio-delay conditions, subjects chose between an FR schedule as the standard alternative and an adjusting delay. In matched delay-delay conditions, subjects chose between a variable-time (VT) schedule as the standard alternative and an adjusting delay. For each subject, the component delays of the VT schedule were chosen to match the mean, the standard deviation, and the approximate shape of the distribution of ratio completion times for the FR schedule of the preceding condition. Four different FR schedules and four matched VT schedules were used for each subject. Every pair of conditions therefore yielded two indifference points, one for an FR schedule and the other for a matched VT schedule. The first indifference point involved an adjusting delay that was equal in value to the FR schedule, and the second an adjusting delay that was equal in value to the VT schedule. To deal with situations such as these, where the delay to reinforcement varies over trials, Mazur (1984, 1986) used the following expansion of Equation 1:

$$V_i = \sum_{j=1}^n p_j \left(\frac{A_i}{1 + K_i D_j} \right), \quad (4)$$

where alternative i consists of n different possible delays, and p_j is the probability that a delay of D_j will occur.

For the present experiment, if the indifference point for each FR schedule is plotted against the indifference point for the corresponding VT schedule, Equation 4 predicts a linear function with a slope of K_r/K_d , as illustrated by the solid line in Figure 1. For this illustration, $K_r = 1.5$ and $K_d = 1.0$.

A change in K_i is, of course, only one of

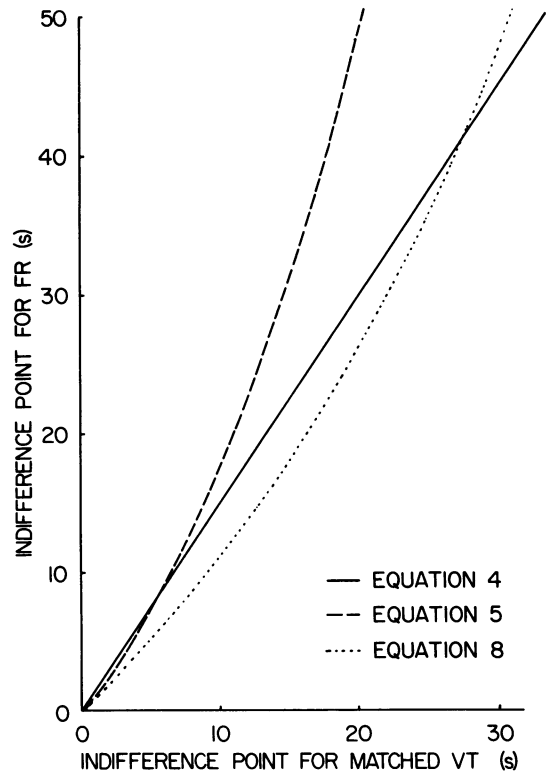


Fig. 1. Representative predictions of Equations 4, 5, and 8. Each point on each function represents a pair of indifference points, one obtained when the standard alternative is an FR schedule (plotted on the y axis) and the other obtained when the standard alternative is a VT schedule with the same mean time to reinforcement (plotted on the x axis).

many ways in which the difference between ratio and time schedules could be represented in a hyperbolic equation for reinforcer delay. Another approach is to raise D_i to some power other than 1.0 for ratio schedules. The possibility of exponentiating D_i to reflect differing effects of delay under differing conditions has been proposed frequently (e.g., Davison, 1969; Green & Snyderman, 1980; Logue, Rodriguez, Peña-Correal, & Mauro, 1984; Rachlin, Logue, Gibbon, & Frankel, 1986). Adding an exponent to D_i in Equation 4 yields

$$V_i = \sum_{j=1}^n p_j \left(\frac{A_i}{1 + K D_j^{B_i}} \right). \quad (5)$$

In Equation 5, B_i is subscripted but K is not, because this equation assumes that K is the same for ratio and time schedules but that B_i

is different. Mazur (1985, 1987) presented evidence that the most appropriate value of B_i for time schedules is 1.0 (or close to 1.0), but it is possible that B_i assumes a value greater than 1.0 for ratio schedules, especially when the instrumental response requires considerable effort. The dashed curve in Figure 1 shows the indifference curve derived from Equation 5, with $B_r = 1.3$ and $B_d = 1.0$ (r and d representing the ratio and time schedules, respectively). More generally, in contrast to the linear function predicted by Equation 4, Equation 5 predicts a curvilinear function whenever $B_r \neq B_d$.

A possible limitation of both Equations 4 and 5 is that they assume V must always be positive for any ratio schedule, no matter how large the ratio and how effortful the instrumental response may be. Intuitively, it seems likely that V might be negative for a very large or effortful FR schedule, indicating that the schedule is aversive despite the opportunity to obtain a reinforcer. Empirically, this idea is supported by Appel's (1963) finding that pigeons will make an instrumental response that allows them to escape from the stimuli associated with a large ratio schedule. To deal with the possibility of negative value with large or effortful ratio schedules, and for other theoretical reasons, we will describe one additional model that is based on a hyperbolic decay function.

On a general level, this model assumes that V , the value of a given alternative, depends on all of the events that occur following a choice of this alternative. The contribution of each event to V depends on (a) what type of event it is, (b) its duration, and (c) its temporal remoteness from the moment of choice. Assume that every event x , whether it is an activity (e.g., eating) or a stimulus (e.g., shock), can be assigned a number, Q_x , that represents the quality of that event—its reinforcing or punishing properties—for a given organism at a given level of deprivation. For instance, Q_x might be a large positive number for eating, a large negative number for shock, and zero for the stimuli associated with a delay interval.

Let t represent the time since the moment of choice, and let Q_t represent the quality of the event occurring at time t . (To be more precise, Q_t could be denoted as $Q_{x,t}$, to indicate that this variable represents the quality of whatever event, x , is occurring at time t . However, for simplicity, the subscript x will be

omitted in the following discussion.) This model assumes that the contribution of the event occurring at time t to V is determined by the product $Q_t \cdot W_t$, where W_t is a weighting factor that depends on the time since the choice response, as expressed in the following hyperbolic equation:

$$W_t = \frac{1}{1 + Kt}. \quad (6)$$

Equation 6 retains the assumption of Equation 1 that the impact of an event on choice declines hyperbolically with delay, but now we are concerned with the weighting of an instantaneous event, not one extended in time. The product $Q_t \cdot W_t$ is the instantaneous contribution of the event occurring at time t to V , which is again the value of an alternative. We can therefore integrate over the duration of that event to estimate its total contribution to V , and, similarly, we can integrate over the entire duration of that alternative (which may be composed of events with different values of Q) to determine its total value:

$$V = \int Q_t W_t dt = \int \frac{Q_t}{1 + Kt} dt. \quad (7)$$

As a simple example, suppose that an animal responds on a ratio schedule for 10 s and then receives 3 s of access to food. Let $K = 1$, $Q_r = -1$, and $Q_f = 100$ (where the subscript r refers to the ratio and f refers to the food). Assuming that the events occurring after the food are negligible, it follows from Equation 7 that

$$\begin{aligned} V &= \int_0^{10} \frac{-1}{1+t} + \int_{10}^{13} \frac{100}{1+t} \\ &= -1 \cdot \ln(1+t) \Big|_0^{10} \\ &\quad + 100 \cdot \ln(1+t) \Big|_{10}^{13} \\ &= 21.7. \end{aligned} \quad (8)$$

If the duration of the food presentation were doubled, Q_f would not be changed, but V would increase to 41.2 because the definite integral for the contribution of food would now be evaluated from 10 s to 16 s.

For choices between two time schedules with different reinforcer durations (e.g., Mazur, 1987), it can be shown that Equation 7 makes the same predictions as Equation 1 if Q_d , the quality factor for the delay interval, is zero. That is, Equation 7 predicts a linear indifference function with a y intercept greater than zero and a slope greater than one. To accommodate the variable times to reinforcement that occurred in the present experiment, we make the same assumptions as in Equations 4 and 5; that is, if n different consequences (n different times to reinforcement in this case) are possible after a choice of a given alternative, we assume that the total value of this alternative is a weighted average of the values of those n possible consequences:

$$V = \sum_{j=1}^n p_j \left(\int \frac{Q_j}{1 + Kt} dt \right). \quad (8)$$

The dotted curve in Figure 1 shows the predictions of Equation 8 with $K = 1$, $Q_f = 100$, $Q_d = 0$, and $Q_r = -0.7$. As can be seen, the predictions are qualitatively similar to those of Equation 5; that is, Equation 8 also predicts a curvilinear function whenever $Q_d > Q_r$. The results of this experiment should therefore serve to discriminate between Equation 4 on one hand and Equations 5 and 8 on the other. If the pattern of results is curvilinear, however, it may be difficult to discriminate between Equations 5 and 8.

METHOD

Subjects

The subjects were 4 White Carneau pigeons maintained at 80% of their free-feeding weights. All had previous experience with a variety of experimental procedures.

Apparatus

The experimental chamber was 33 cm long, 31 cm wide, and 32 cm high. Three response keys, each 2 cm in diameter, were mounted on the front wall of the chamber, with their centers 10 cm apart and 24 cm above the floor. Each key could be transilluminated with either red, white, or green light produced by two 2-W bulbs mounted behind the keys. Mounted on the back of the keys were trays into which standard lead weights could be placed to reg-

ulate the force necessary to operate the keys. A force of approximately 0.18 N was required to operate the left key, and a force of approximately 0.48 N was required to operate the right key. When either key was illuminated, an effective response on that key produced a feedback click; no feedback was delivered for a peck at a dark key. A hopper below the center key, 9 cm above the floor, provided controlled access to mixed grain. Two 6-W white lights above the hopper were illuminated when the hopper was raised to make grain available. Six 6-W lights (two white, two red, and two green) were mounted on the back wall of the chamber just below the ceiling. The chamber was enclosed in a sound-attenuating box that contained an air blower for ventilation and a speaker producing continuous white noise to mask extraneous sounds. A PDP-8[®] computer in another room used a SuperSKED[®] program to control stimuli and to record responses.

Procedure

The experiment consisted of eight conditions. Throughout the experiment, when the right key was illuminated it was green, and it represented the standard alternative; when the left key was illuminated it was red, and it represented the adjusting alternative. The white houselights were illuminated throughout a session except during reinforcement periods. Throughout the experiment, reinforcement for either alternative was 3-s access to grain. The intertrial interval (ITI) for each alternative was 30 s. Each experimental session lasted for 60 trials or 90 min, whichever came first. The 60 trials were divided into blocks of four trials. Within each block, the first two trials were forced trials and the next two were choice trials, as described below.

FT-FR choices (Conditions 1, 3, 5, and 7). These four conditions required the completion of a specified ratio on the standard (green) key. These conditions differed from each other only in the size of the ratio requirement on the green key. Figure 2 diagrams the sequence of events on a free-choice trial. After a 30-s ITI during which only the white houselights were lit, a trial began with the illumination of the white center key. A peck on this key was required so that the subject's head would not be close to one of the side keys when the choice period began. A center key peck darkened this key

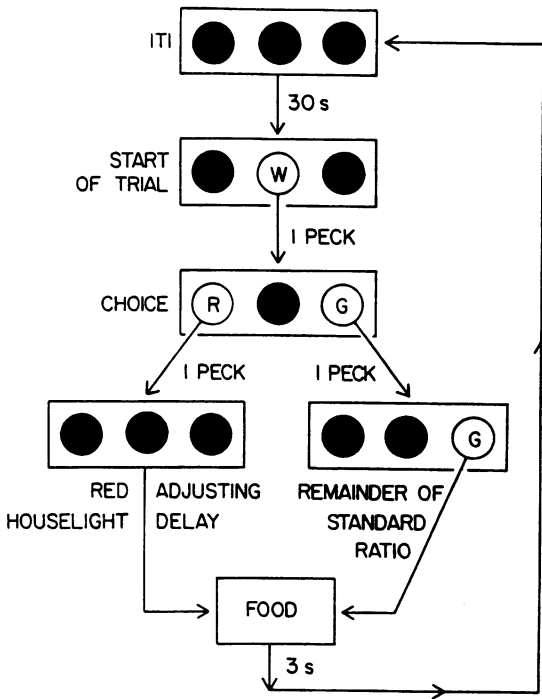


Fig. 2. A schematic diagram of the two possible sequences of events that could occur on a free-choice trial, depending on whether the red (R) or green (G) key was pecked.

and illuminated both side keys, the left key red and the right key green. As soon as the pigeon pecked one of the two colored keys, it was committed to its choice. If the pigeon pecked the green key, the red key immediately extinguished, and the pigeon was required to complete the ratio on the green key before another trial began. Completion of the ratio resulted in the darkening of the keylight and the white houselights and in the presentation of grain. After reinforcement, the next ITI began. If the pigeon pecked the red key, both keylights immediately extinguished and the adjusting delay began, during which the red houselights were lit. At the end of the adjusting delay, all houselights were extinguished and the reinforcer was presented. Again, after reinforcement, the next ITI began.

The procedure on forced trials was the same as on choice trials, except that only one side key was illuminated, either green or red, after a center key peck, and the subject was required to peck the illuminated key (and, if the green key, then to complete the ratio). Of the two

Table 1

Order of conditions, with the mean times to reinforcement for the standard and adjusting alternatives (in seconds), and the number of sessions needed to satisfy the stability criteria.

Condition	Standard schedule	Mean time to reinforcement		Number of sessions
		Standard	Adjusting	
Subject 1				
1	FR 25	5.38	6.32	16
2	VT	5.38	5.82	14
3	FR 50	14.89	17.32	16
4	VT	14.89	17.23	26
5	FR 75	20.75	27.96	26
6	VT	20.75	22.33	21
7	FR 100	25.36	40.37	23
8	VT	25.36	28.39	16
Subject 2				
1	FR 25	6.30	9.35	16
2	VT	6.30	5.06	14
3	FR 50	12.18	18.13	19
4	VT	12.18	12.29	27
5	FR 75	18.93	96.16	17
6	VT	18.93	24.06	19
7	FR 5	1.19	1.42	23
8	VT	1.19	0.05	24
Subject 3				
1	FR 25	8.16	15.08	28
2	VT	8.16	7.68	23
3	FR 50	20.12	54.84	18
4	VT	20.12	16.58	14
5	FR 5	1.89	2.77	37
6	VT	1.89	2.86	26
7	FR 15	7.12	12.76	19
8	VT	7.12	9.69	26
Subject 4				
1	FR 25	18.26	25.70	34
2	VT	18.26	18.74	23
3	FR 50	31.21	57.07	21
4	VT	31.21	33.56	26
5	FR 5	1.43	4.65	24
6	VT	1.43	3.21	24
7	FR 15	4.80	8.62	14
8	VT	4.80	6.56	19

forced trials in each block, one involved the green key and the other the red key. The order of presentation of these two colors varied randomly across blocks.

After every two choice trials, the delay for the adjusting key might be changed. If a subject had chosen the adjusting key on both choice trials, the adjusting delay was increased by 1 s. If the subject had chosen the standard key on both trials, the adjusting delay was decreased by 1 s, unless it was already zero. If the subject had chosen each key on one trial,

no change was made in the adjusting delay. In all three cases, this adjusting delay remained in effect for the next block of four trials. At the start of the first session of the experiment, the adjusting delays were set at zero. At the start of every other session, the adjusting delay was determined by these rules as if it were a continuation of the preceding session.

Column 2 of Table 1 shows the ratio requirements used for each subject in each condition and the order in which the ratios were tested. All conditions lasted for a minimum of 14 sessions and were terminated for each subject individually when several stability criteria were met. To assess stability, the mean delay on the adjusting key was calculated for each session. The results of the first four sessions of a condition were not used, and a condition was terminated when the following three criteria were met using the data from all subsequent sessions: (a) neither the highest nor the lowest single-session mean of a condition could occur in the last five sessions of a condition; (b) the mean adjusting delay across the last five sessions could not be the highest nor the lowest five-session mean of the condition; and (c) the mean adjusting delay across the last five sessions could not differ from the mean of the preceding five sessions by more than 10%.

FT-VT choices (Conditions 2, 4, 6, and 8). An FT-VT choice condition followed each FT-FR condition in order to control for the variability in completion times of the FR schedules in the preceding condition. The components of the VT schedule were selected to approximate the distribution of FR completion times from the preceding condition, using the following procedure. For each subject, all FR completion times from the five sessions that satisfied the stability criteria were ranked from lowest to highest, creating a distribution of approximately 150 durations (with the total number of durations ranging from 135 to 160). (For 3 subjects, one extremely long completion time was eliminated in one condition.) The distribution was then divided into 30 intervals, each containing approximately five durations. The mean duration of each interval was used as one of the 30 components of the VT schedule, with the following exception. Durations at the extremes of the VT distribution were altered slightly if necessary to equate the mean, standard deviation, and the approximate shape of

the VT distribution with those of the corresponding FR completion-time distribution.

The FT-VT conditions differed from the FT-FR conditions in only two ways: (a) the VT schedule replaced the FR schedule on the standard key; and (b) after a single response on the green (standard) key, both keys immediately extinguished and the VT schedule began, during which the green houselights were lit. After the standard delay, all houselights were extinguished, and reinforcement began. As in the FT-FR conditions, an effective response on the red key required a force of 0.18 N, and an effective response on the green key required a force of 0.48 N.

RESULTS

The right-most column of Table 1 lists the number of sessions needed for each subject to satisfy the stability criteria in each condition. All analyses were based on the five sessions that satisfied the stability criteria, and the average value of the adjusting delays of the five sessions was used as a measure of the indifference point for that condition.

Table 1 also presents the mean standard and adjusting delays in all conditions for each bird. For example, for Subject 1 in Condition 1, the FR was 25, the mean time to complete this ratio was 5.38 s, and the adjusting delay value obtained (the indifference point) was 6.32 s. For Condition 2 of Subject 1, the average time to reinforcement on the VT schedule was 5.38 s (a duration chosen to equal the mean ratio completion time of the preceding condition, as explained in the Method section), and the corresponding adjusting delay value was 5.82 s. Table 1 shows that in 15 of 16 cases, the adjusting delay was at least slightly longer when the alternative was an FR schedule than when it was a VT schedule.

Figure 3 shows that the experimental design ensured a close correspondence between the distribution of components of each VT schedule and the distribution of ratio completion times of the previous FT-FR condition. In each panel, the plotted line shows the distribution of ratio completion times for Subject 1 (graphed as a cumulative probability function), and the filled circles are the 30 components of the corresponding VT schedule (also plotted as a cumulative probability function). As can be seen, the distributions of times be-

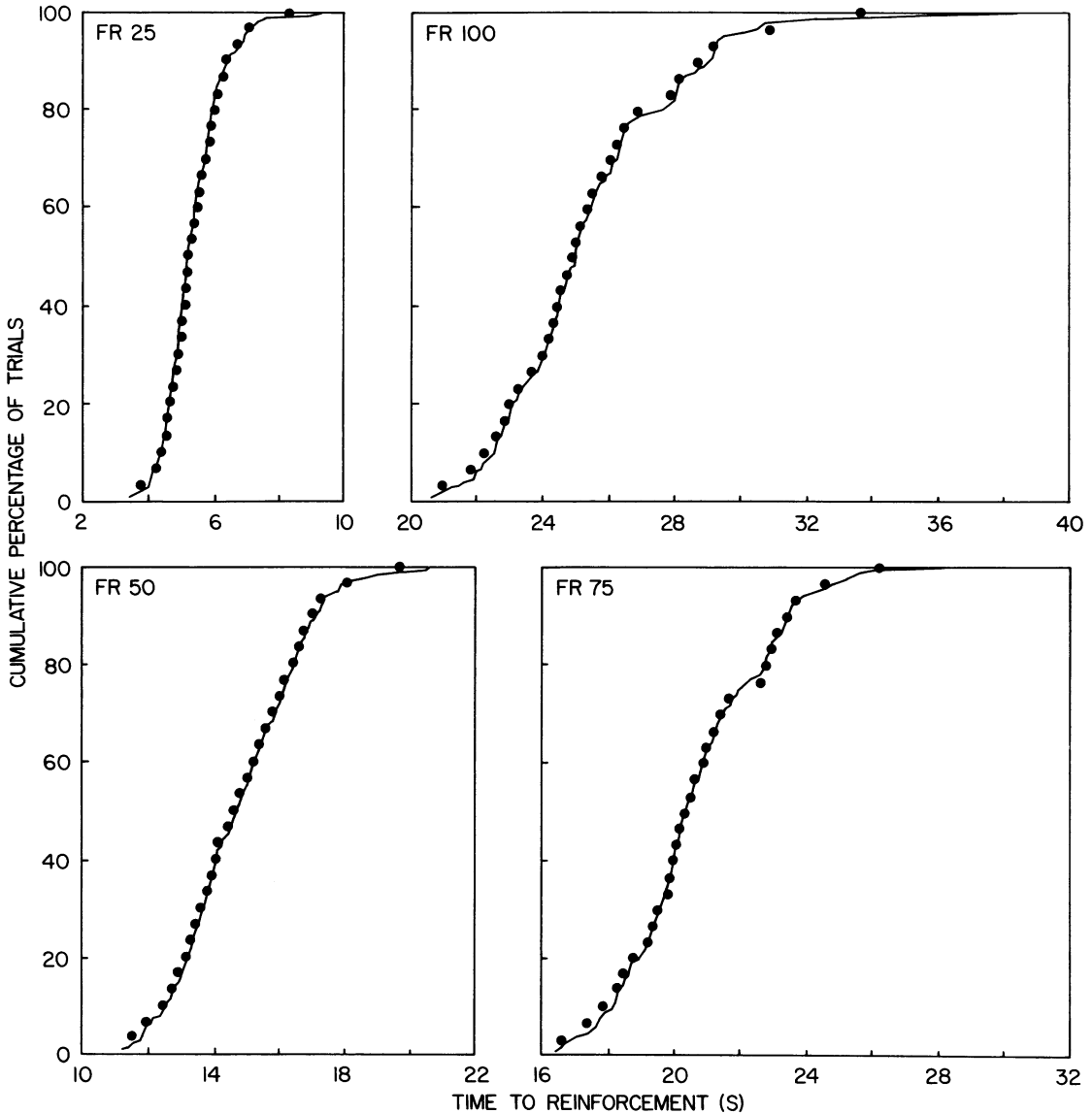


Fig. 3. For Subject 1, times to reinforcement on the FR schedules (solid lines) and on the matched VT schedules (filled circles) are plotted as cumulative probability functions. Each panel shows a function for one FR schedule and for the corresponding VT schedule.

tween a choice response and reinforcement on the standard schedule were very similar in each pair of conditions. In addition, a comparison of the distributions in the four panels shows that the variability of the ratio completion times grew larger as the ratio requirement increased from FR 25 to FR 100. The distributions for the other subjects were comparable.

For each subject, Figure 4 presents the mean

FR indifference points as a function of the mean VT indifference points, with each point representing a matched pair of FR and VT conditions. If the FR and VT indifference points were the same within each pair, the indifference points would fall on the solid diagonal lines. As indicated in Table 1, all but one of the 16 points fell at least slightly above this line, and the distance between the data

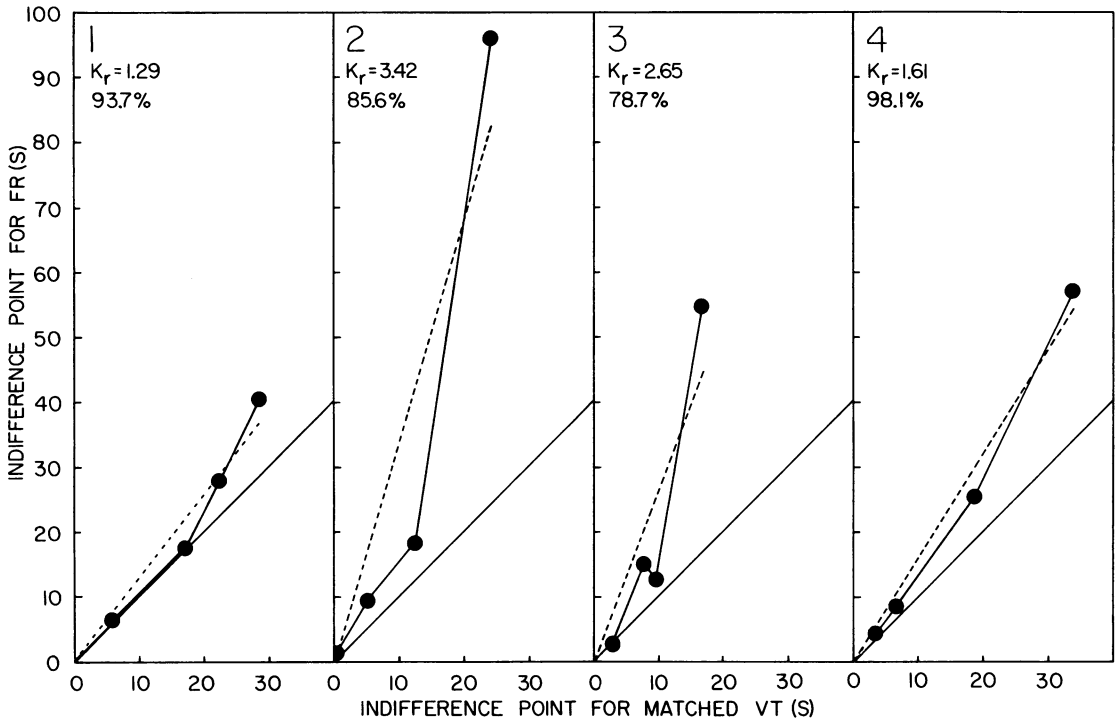


Fig. 4. For each subject, each data point represents two indifference points, one obtained in an FR schedule (y axis) and the other in the corresponding VT schedule (x axis). The points would fall on the solid diagonal line if the indifference points were the same in an FR schedule and in its matched VT schedule. Points above the line indicate a preference for the VT schedule. The dotted lines are the best fitting predictions of Equation 4, and each panel shows the values of K_r and the percentage of variance accounted for by Equation 4.

points and the line grew larger with increasing ratio sizes. These departures from the diagonal line indicate a preference for the delays over the ratio schedules.

These results were compared to the predictions of the three equations discussed in the introduction. For each equation, an iterative procedure was used to find the value of one free parameter that produced the best least squares fit between predictions and results. For the predictions of Equation 4, K_r was treated as a free parameter, and K_d was set equal to 1.0. The dotted lines in Figure 4 are the best least squares fits for each subject, and the value of K_r and the percentage of variance accounted for by Equation 4 are shown in each panel. Notice that although Equation 4 predicts a linear relation, the data points for each subject followed a pattern that was at least slightly curvilinear.

Figure 5 presents the same data points, but here they are compared to the best fitting predictions of Equations 5 and 8. The dashed

curves are the predictions of Equation 5, with K and B_d set equal to 1.0 and with B_r treated as a free parameter. The solid curves are the predictions of Equation 8, with Q_r treated as a free parameter and with $K = 1.0$, $Q_f = 100$, and $Q_d = 0$. The value chosen for Q_f is completely arbitrary, because identical predictions would be generated if both Q_f and Q_r were multiplied by the same positive constant, as long as $Q_d = 0$. Therefore, the predictions from Equations 5 and 8 were both obtained by using a single free parameter (as were those of Equation 4 in Figure 4). The predictions of both equations were quite good, but Equation 8 accounted for a slightly larger percentage of the variance for each of the 4 subjects.

In this experiment, the latency to make each response on either the green (standard) or red (adjusting) key was recorded, and latencies during the trials that satisfied the stability criteria were analyzed. For each subject and each condition, median response latencies were calculated for the standard and adjusting keys.

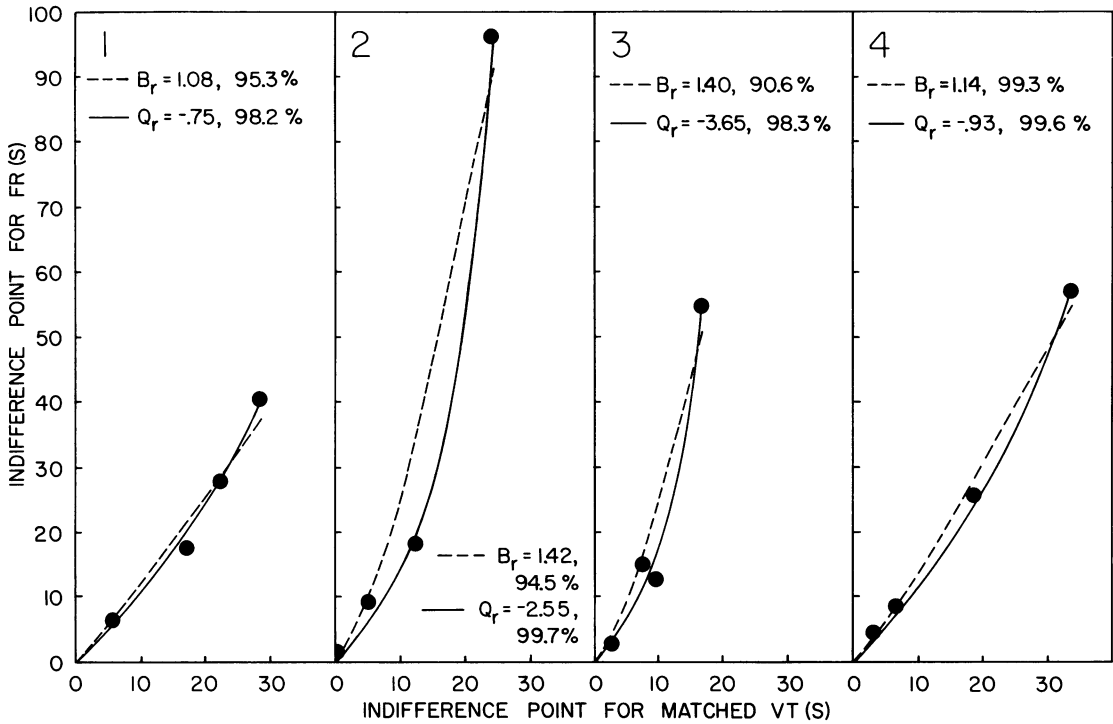


Fig. 5. The data points from Figure 4 are replotted and compared to the best fitting predictions of Equation 5 (dashed curves) and Equation 8 (solid curves). In each panel, the best fitting values of B_r and Q_r and the percentages of variance accounted for by each equation are shown.

The median latencies ranged from 0.7 s to 4.6 s on the standard key and from 0.7 s to 5.3 s on the adjusting key, with the longest latencies occurring in conditions in which the standard alternative was a large FR schedule. Very long latencies occurred on a few trials: 0.3% of the response latencies were greater than 60 s. Of these long latencies, 63% preceded responses on a FR schedule. Nevertheless, because the great majority of the response latencies were only a few seconds or less in duration (and therefore constituted only a small proportion of the total time to reinforcement), the effect of these latencies on the measured indifference points, if any, was probably minimal.

DISCUSSION

As in the studies of Mazur (1986) and Grossbard and Mazur (1986), the present experiment demonstrated a preference for simple delays over ratio schedules with the same average time between a choice response and reinforcer delivery. With the largest ratio sizes in

this experiment, this preference was extreme for some subjects. For example, when both an FR and a VT schedule imposed a delay of about 20 s between a choice response and reinforcement, Subject 3 reached an indifference point of about 17 s for the VT schedule and about 55 s for the FR schedule. This result implies that the FR schedule had considerably less value than the VT schedule, because a reinforcer delayed 55 s has considerably less value than one delayed 17 s (see, e.g., Mazur, 1987). This degree of preference for delays over FR schedules was greater than that obtained in the studies of Mazur (1986) and Grossbard and Mazur (1986), perhaps largely because of the greater response effort required by the FR schedules in the present experiment.

Two procedural features that might have affected preference in this experiment should be considered. First, throughout the experiment, greater force was required to make a choice response on the standard key (0.48 N) than on the adjusting key (0.18 N). This feature introduced an unnecessary asymmetry

within conditions that could be avoided in future research simply by requiring an equally effortful choice response for both alternatives. However, this asymmetry was present both in the FR conditions and the VT conditions, so it cannot account for the shorter indifference points obtained in the VT conditions. Second, different stimuli were associated with the FR and VT schedules. The standard key was transilluminated with green light throughout the FR schedules; on the VT schedules, the green key was darkened after the choice response, and the green houselights were lit until the the reinforcer was delivered. It seems unlikely, however, that this difference in stimuli was responsible for the shorter indifference points obtained with the VT schedules, for the following reason. The same types of stimulus changes were used in previous studies that found only modest preferences for time schedules over ratio schedules (Grossbard & Mazur, 1986; Mazur, 1986). Compared to these studies, the present study required more forceful responses on the ratio schedules, and greater preference for the time schedules was found. This increased preference cannot be attributed to the stimulus lights. This suggests that the large preference for the VT schedules in the present study was due mainly to the absence of a response requirement, rather than to the absence of the green keylight during the delay interval.

One other feature of the present experiment was the use of VT rather than FT schedules to control for the variability in ratio completion times on the FR schedules. This feature eliminated the possibility that any observed preference for one schedule over the other might be due to a difference in the variability of times between choice and reinforcement. The present procedure also controlled for side and key-color bias, because both the FR and VT schedules were associated with the green, right key, and both were compared to an adjusting delay associated with the red, left key. The results therefore make a strong case that simple delays are preferred over ratio schedules that impose equal times between a choice response and reinforcement. The results contradict the notion that the presence or absence of a response requirement is inconsequential if times to reinforcement are the same (Neuringer & Schneider, 1968).

An important finding of the present exper-

iment was that the functions relating the FR and VT indifference points appeared to be curvilinear for every subject. This curvilinearity in the empirical functions can be demonstrated in at least two ways. First, the deviations of the data points from the linear functions predicted by Equation 4 were not random but systematic, with the predicted FR schedule durations being too long for the smaller FR schedules and too short for the largest ratio schedules. Second, Equations 5 and 8, both of which predict curvilinear functions, accounted for more of the variance in the data points for each of the 4 subjects than did Equation 4. For every subject, Equation 4 accounted for the smallest percentage of the variance, Equation 5 for a larger percentage, and Equation 8 for the largest percentage. Averaged across subjects, Equations 4, 5, and 8 accounted for 89.0%, 94.9%, and 99.0% of the variance, respectively.

The curvilinearity in the empirical functions differs from the patterns obtained in the experiments of Mazur (1986) and Grossbard and Mazur (1986). These two experiments obtained approximately linear indifference functions between the mean times to complete FR schedules and FT schedules. This difference between the present study and the previous ones could be due to the greater force necessary to operate the FR key or to the use of VT schedules that matched the variability in ratio completion times. In any case, this curvilinearity suggests that Equation 4 cannot accommodate the difference between delays and ratio schedules by using a different value of K_i for each. More generally, the curvilinearity is inconsistent with any theory that says that for a series of FR schedules, the equally preferred delays will be longer than the mean ratio completion times by a constant proportion. Instead, the results indicate that the difference between FR completion times and equally preferred reinforcer delays increases as the size of the FR increases.

The results are more consistent with Equations 5 and 8, both of which predict curvilinear functions. Because Equation 8 accounted for a greater percentage of the variance for each subject than did Equation 5, this experiment gives a slight indication that Equation 8 may offer a more appropriate way to account for the effects of an effortful response requirement. The differences in the predictions of the

two equations were small, however, so it is not possible to draw a firm conclusion about their relative merits. Of these two approaches, the strategy of exponentiating D , as described by Equation 5, has more precedents in the literature. Several writers have suggested that differential sensitivity to reinforcer delays can be described by using different exponents for delay (e.g., Davison, 1969; Logue, 1988). Yet although the notation and mathematics of Equation 8 may be more complex, the model it represents is actually quite simple from a conceptual standpoint. The model states, first, that every reinforcer and every class of behavior has a quality, as represented by Q , that is either positive, negative, or zero. This idea is similar to the approach used by Miller (1976) in his analysis of pigeons' choices among different types of grain. It also bears a resemblance to the position of Premack (1965, 1971) and others (e.g., Mazur, 1975; Staddon, 1979; Vaughan, 1985) who have claimed that all types of behavior and all stimuli can be measured on a common, unidimensional scale that reflects their reinforcing or punishing capacities. Second, the model described by Equation 8 assumes that an event's reinforcing or punishing effect also depends on its duration and its delay. Experiments demonstrating the effects of duration and delay are numerous. The studies cited in the Introduction suggest that the relation between delay and value can be described by a hyperbolic equation, which is why this model incorporates a hyperbolic weighting function for delay (Equation 6).

Perhaps the most straightforward way to test empirically between Equations 5 and 8 would be to determine unambiguously whether a long FR schedule with a forceful response can have negative value (i.e., whether such a schedule can be aversive). Equation 8 predicts that such an FR schedule can have negative value, whereas Equation 5 predicts that its value can never drop below zero. In this regard, Appel's (1963) study on the aversive characteristics of stimuli associated with long FR schedules is suggestive evidence for Equation 8, but more convincing tests of this prediction are needed.

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