*TYPICAL DELAY DETERMINES WAITING
TIME ON PERIODIC-FOOD SCHEDULES:
STATIC AND DYNAMIC TESTS*

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Pigeons and other animals soon learn to wait (pause) after food delivery on periodic-food schedules before resuming the food-rewarded response. Under most conditions the steady-state duration of the average waiting time, t , is a linear function of the typical interfood interval. We describe three experiments designed to explore the limits of this process. In all experiments, t was associated with one key color and the subsequent food delay, T , with another. In the first experiment, we compared the relation between t (waiting time) and T (food delay) under two conditions: when T was held constant, and when T was an inverse function of t . The pigeons could maximize the rate of food delivery under the first condition by setting t to a consistently short value; optimal behavior under the second condition required a linear relation with unit slope between t and T . Despite this difference in optimal policy, the pigeons in both cases showed the same linear relation, with slope less than one, between t and T . This result was confirmed in a second parametric experiment that added a third condition, in which $T + t$ was held constant. Linear waiting appears to be an obligatory rule for pigeons. In a third experiment we arranged for a multiplicative relation between t and T (positive feedback), and produced either very short or very long waiting times as predicted by a quasi-dynamic model in which waiting time is strongly determined by the just-preceding food delay.

Key words: temporal discrimination, feedback, quasi-dynamic model, obligatory rule, pigeons

When hungry pigeons or rats are allowed to eat only at fixed intervals (i.e., on FI schedules), their behavior adjusts to the typical time between feedings. If a response such as key pecking or lever pressing is required to produce food, the time to the first response after a feeding, postreinforcement pause or *waiting time*, is roughly proportional to the typical interfood interval (cf. Ferster & Skinner, 1957; Schneider, 1969), with a constant of proportionality considerably less than unity (i.e., the animals act prior to the availability of the food).

Pigeons and rats always show this highly adaptive waiting pattern when food delivery

is simply periodic. However, there are limits on their ability to wait appropriately under other conditions. For example, when food delivery is contingent upon a minimum inter-response time (spaced-responding schedules), pigeons have difficulty spacing pecks more than approximately 20 s apart (Staddon, 1965) although they can wait up to about 70 s when the required response is perch hopping (Lejeune & Jasselette, 1986). Pigeons fail to wait long enough on spaced-responding schedules, whereas under other conditions they wait too long. For example, on schedules where the time to food following the first postfood response is fixed (response-initiated FI schedules) they will wait for substantial periods after food before making the first peck, even though every second of waiting unnecessarily delays food (Shull, 1970).

The first two experiments in the present series pursue further the limits on pigeons' ability to adjust their waiting time: Under what conditions is waiting *obligatory* and when is it *facultative*? Is the relation between waiting time and typical interfood interval systematically different under schedules in which optimal performance requires different relations (facultative) or is it always (or nearly always) the same, no matter how maladaptive the result

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(obligatory)? The first experiment compared performance on a schedule resembling response-initiated FI (the *fixed* condition) and a schedule in which the time to food after the first response depends on the waiting time (*dependent* condition). The second experiment was a systematic replication of the first, with the addition of a third condition in which the interfood interval was essentially independent of the animal's waiting time (*clamped* condition). We found in both experiments that our pigeons showed essentially the same linear relation between average waiting time and typical interfood interval, no matter what the scheduled relation between waiting time and time to subsequent food. In other words, under the range of conditions studied here, linear waiting seems to be an obligatory reaction to delayed food. The third experiment tested predictions from a simple quasi-dynamic model of the waiting process.

EXPERIMENT 1: WAITING TIME VERSUS FOOD DELAY WITH FIXED AND DEPENDENT DELAYS

In the first two experiments we explore the implications of the view that waiting is an obligatory reaction to food delay. We used the simplest possible procedure: The pigeon was provided with signals for the waiting period (a red keylight) and for the subsequent food delay (a green light). A waiting period began after each food delivery and was terminated by the first key peck, which changed the keylight from red to green. Food was delivered after a predetermined delay in green.

The logic of the experiments is as follows: In the fixed condition, the food delay (time in green: T) was constant. Hence, the time between food deliveries depended entirely upon the waiting time (time in red: t). Because waiting time is always under the control of the animal, the optimal strategy in the fixed condition is for the animal to respond immediately after food, initiating the fixed delay as soon as possible. In the dependent condition, however, the delay time, T , is inversely related to the waiting time, t : $T = K/(t + 1)$, where K is a parameter; consequently, interfood interval ($t + T$) is a U-shaped function of t , being shortest when $t = K^{1/2} - 1$, which, given that $t + 1 = K/T$ (by the schedule constraint), implies a relation between waiting time and food delay

of the form $t = T - 1$ as K is varied, if the subject is behaving optimally. Thus, if waiting time is sensitive to the contingencies, rather than being determined only by the typical food delay, the relation between t and T should be very different under these two conditions: t should be short and independent of T for the fixed condition, but proportional to T for the dependent condition. We made this comparison in the first experiment, looking at the relation between waiting time and food delay at two parameter values under each condition (four conditions in all).

METHOD

Subjects

Four homing pigeons (*Columba livia*) of local stock, all with extensive histories on various forms of nontemporal concurrent operant discrimination, and maintained at 80% of their free-feeding weights, served as subjects.

Apparatus

Pigeons were studied in a one-key, cubic Skinner box (33 cm on a side) constructed in the workshops of the Psychologisches Institut, Ruhr-Universität. A single response key of 2.5 cm diameter that could be transilluminated with red or green light was situated in the center of the back panel, 21 cm above the floor. The 2-cm diameter food-hopper opening was 7 cm above the floor in the center of the back wall. Food reward consisted of 2-s access to mixed grain. A Commodore® microcomputer controlled experimental events and recorded the time of each key peck. Data were transferred to a larger computer for analysis.

Procedure

Both conditions followed the same repeating cycle: After food delivery the single response key was illuminated red. The first key peck extinguished the red light and turned the key green (time in red, set by the pigeon, is denoted by t)—no additional key peck was required; pecks on the green key were recorded but had no scheduled consequences. After an additional length of time T , set by the apparatus, the green light was extinguished and 2-s access to mixed grain followed. After food delivery, the response key was once again red (i.e., the next cycle followed immediately without any intertrial interval). Thus, an experimental session consisted of several cycles in each of which

Table 1
Experiment 1: blocked conditions.

Condition (in order)	Number of sessions	Parameter value ^a	Median t^b
Bird 15			
Fixed	6	2 s	1.435
Fixed	13	10 s	2.880
Dependent	9	20 s ²	1.410
Dependent	10	5 s ²	1.040
Bird 20			
Fixed	7	10 s	5.700
Fixed	15	2 s	0.930
Dependent	9	5 s ²	1.050
Dependent	10	20 s ²	2.050
Bird 195			
Dependent	7	5 s ²	1.340
Dependent	15	20 s ²	3.480
Fixed	10	2 s	0.990
Fixed	8	10 s	2.690
Bird 280			
Dependent	8	20 s ²	2.780
Dependent	15	5 s ²	1.800
Fixed	7	10 s	3.230
Fixed	8	2 s	0.810

^a Parameters are: dependent, K ; fixed, T . Procedures are defined as follows: fixed, $T = \text{constant}$; dependent, $T = K/(t + 1)$.

^b Median of daily medians.

the key was first red, then (after a peck) green, followed by food. Sessions ended after 100 cycles.

In the first experiment we studied the effect on time t (the waiting time in red) of two rules relating t to T (delay time to food in the presence of green): fixed (T constant— T is a parameter) and dependent (T inversely related to t : $T = K/(t + 1)$, where K is a parameter). We looked at two different parameter values under each of these two schedules for each pigeon. The sequence of conditions and number of sessions for each pigeon, with parameter values, are shown in Table 1.

RESULTS

The data of interest here are the times to first response in red (i.e., the waiting time, t) as a function of food delay in green (T). Figure 1 shows the average t values for each pigeon under the two fixed and two dependent conditions as a function of the average food delay, T (the same data also appear in Table 1). The individual birds are indicated by letters (a is Bird 15, b is Bird 20, etc.). Conditions are identifiable by the constraints on individual

Fig. 1. Waiting time, t , in red, as a function of food delay, T , in green for the two fixed and two dependent conditions in Experiment 1. The individual birds are denoted by small letters (a, b, c, and d); the points are medians of daily medians, averaged across all exposures to a condition (first 10 intervals each day excluded). The conditions are identifiable by the arrangement of the individual data points: vertically (fixed) or along a hyperbola (dependent). The two straight lines connect the averages for the two conditions.

data points: the a, b, c, and d points lie along vertical lines (not drawn) at 2 and 10 s for the two fixed conditions and on hyperbolas for the two dependent conditions. The two solid lines connect the averages for the fixed and dependent conditions. The data provide no evidence that the two procedures had different effects. Although there are too few data points to be sure of the form of the relation between t and T , all four average points lie on about the same function, which appears to be approximately linear, with a small positive intercept on the t axis (i.e., a minimum waiting time). The best fitting line (fitted by eye, because the data are not suitable for standard regression methods because of the different constraints between T and t) is $t = 0.29T + 0.6$.

DISCUSSION

Even when very different waiting policies are required to maximize food rate, the pigeons adjusted their waiting time, t , as the same linear function of food delay, T . The empirical result, $t = 0.29T + 0.6$, is a line with a slope well below the slope of the optimal function for the dependent procedure, $t = T - 1$, but

Fig. 2. Waiting time, t , in red in each cycle for transitional sessions for the 4 pigeons. In each graph, the left side is the last session under one condition, and the right side the first under the the next condition. T signifies the value of the fixed delay for fixed conditions; K signifies the value of the parameter in the dependent conditions.

well above the zero slope required for optimal performance under the fixed condition. The pigeons' performance was optimal for neither procedure, but seems instead to follow the same linear waiting function for both.

It is a matter of convenience whether we represent these data in terms of a relation between food delay, T , and the dependent variable, t , or in terms of a relation between interfood interval, $T + t$, and t . The latter relation is more usual on FI schedules. Transforming the line fitted to the average data into the form $t = A(t + T) + B$ yields $A = 0.22$ and $B = 0.43$ s.¹

The slope of the linear-waiting function in this experiment, A , is less than the pause as a fraction of interfood interval typically reported for fixed-interval schedules, which is usually given as 0.5 or more (e.g., Richelle & Lejeune, 1980; Schneider, 1969). One reason is that we measured the time just to the first peck after food, rather than time to the first group of pecks or time to an estimated "break point," which must always give longer pause estimates. The second reason may be the relatively

brief exposure of these relatively inexperienced pigeons to the schedule: Our birds had only between 6 and 15 sessions of exposure to each condition, whereas in the earlier fixed-interval studies animals usually had 30 or more sessions at each parameter value. We chose our condition durations for three reasons: (a) To test the hypothesis requires the animals to be exposed to several parameter values under each condition, hence each condition cannot be too long if the experiment is to be completed within a reasonable time; (b) in nature the environment changes relatively rapidly, hence pigeons' ability to adjust to relatively rapid changes is of intrinsic interest; and (c) we saw no evidence for systematic changes in performance after the first few cycles of each session, or across sessions within a condition.

Data supporting conclusion (c) are shown in Figure 2. The figure shows waiting time, t , in every cycle for the eight sessions in which there was a transition from one type of procedure to another for the 4 pigeons. Thus, the bottom graph shows the last day of the fixed condition, with $T = 10$, and the first day of the succeeding dependent condition, with $K = 20$ for Bird 15. It is clear from the graph that t for the first interval is very long (this was true for almost every session for every animal), and for this particular transition, t is slightly

¹ The algebra is as follows. From the data we have $t = aT + b$, where $a = 0.29$ and $b = 0.6$. If the theoretical relation (in terms of the typical time-to-food) is $t = A(t + T) + B$, then it follows that $A = a/(1 + a)$ and $B = b(1 - a)$.

shorter under the dependent condition; but there is no evidence for any gradual change across the first day of the new condition. The other graphs lead to a similar conclusion. The data are quite variable, but the effect of the new procedure seems to be relatively rapid.

Figure 3 shows the daily average waiting times throughout Experiment 1. In some cases, there seems to be an effect of the transition after the first day: Bird 15, Days 2 to 5 for $T = 10$, Days 2 and 3 of $K = 5$; Bird 20, Days 2 and 3 of $T = 10$; Bird 195, Days 2 to 6 of $K = 20$, Day 2 of $T = 10$; Bird 280, Days 2 and 3 of $T = 10$. However, none of these effects are statistically different from simple random variation. There may be an effect of continued experience with the procedure, but the variation is too great to allow us to demonstrate it here.

The lack of evidence for systematic changes in t after the first few cycles of a session, and our need to look at additional parameter values and procedures, led us to change procedures on a daily basis in Experiment 2.

EXPERIMENT 2: WAITING TIME VERSUS FOOD DELAY WITH FIXED, DEPENDENT, AND CLAMPED DELAYS

The objective of this experiment was the same as the first: to see if pigeons varied the relation between waiting time and typical time to food under different delay conditions. We used the same general procedure as before; differences included a third procedure, the clamped condition, for which food delay, T , was complementary to waiting time, t : $t + T = C$, a constant, so that interfood interval was independent of t for all $t < C$ (this procedure resembles what has been called a conjunctive fixed-ratio 1, fixed-time schedule: Shull, 1970; Staddon & Frank, 1975; see also Innis & Honig, 1979). Also, conditions were changed daily, rather than remaining constant across several days.

METHOD

Subjects and apparatus were the same as in Experiment 1.

Procedure

The fixed and dependent procedures were the same as in Experiment 1. In addition, we

Fig. 3. Average waiting time (daily medians), t , in red for the 4 pigeons for each session of every condition.

used a clamped procedure, in which total interfood interval was held constant: $t + T = C$; thus, if waiting time in red, t , was 5 s and C was 8 s, food delay in green, T , was 3 s. If the animal waited longer than C , then interfood interval was equal to t , and the animal received a flash of green and food simultaneously (t was rarely greater than C). We looked at four parameter values under the clamped condition and two each under the fixed and dependent conditions, a total of eight different conditions for each pigeon. These eight were presented in a pseudorandom sequence, a different condition each day. The conditions given to each bird, the number of sessions under each, and the average t values obtained are shown in Table 2.

RESULTS

Figure 4 shows the average waiting time as a function of average food delay for all birds and all conditions in Experiment 2. The individual birds are indicated by letters, as in the previous experiment. Constraint lines for all three conditions are also shown: Individual data points for the four clamped conditions lie on the diagonal lines, points from the two fixed

Table 2
Experiment 2: intercalated conditions.

Condition	Number of sessions	Parameter value ^a	Median t^b
Bird 15			
Clamped	7	3 s	0.89
Clamped	6	8 s	1.64
Clamped	6	13 s	2.90
Clamped	7	18 s	4.00
Fixed	6	6 s	1.45
Fixed	7	14 s	3.62
Dependent	6	40 s ²	2.40
Dependent	7	60 s ²	3.40
Bird 20			
Clamped	7	3 s	0.67
Clamped	7	8 s	2.37
Clamped	7	13 s	3.38
Clamped	6	18 s	5.50
Fixed	6	6 s	1.78
Fixed	6	14 s	6.79
Dependent	6	40 s ²	3.58
Dependent	6	60 s ²	4.87
Bird 195			
Clamped	6	3 s	0.91
Clamped	7	8 s	2.38
Clamped	6	13 s	4.49
Clamped	7	18 s	5.23
Fixed	7	6 s	1.50
Fixed	8	14 s	5.83
Dependent	6	40 s ²	3.87
Dependent	8	60 s ²	4.55
Bird 280			
Clamped	7	3 s	0.91
Clamped	7	8 s	2.03
Clamped	6	13 s	4.08
Clamped	7	18 s	6.10
Fixed	6	6 s	2.71
Fixed	8	14 s	6.36
Dependent	8	40 s ²	4.60
Dependent	6	60 s ²	4.11

^a Parameters are: dependent, K ; clamped, $t + T$; fixed, T .

^b Median of daily medians.

conditions lie on vertical lines, and points for the two dependent conditions on hyperbolas.

The results are similar to those of Experiment 1. All the average points lie close to the same linear function. The straight line best fit by eye is $t = 0.45T - 0.5$, a steeper slope than we found in Experiment 1. Because of the constraints on T , we could test this difference statistically only for the fixed conditions in Experiments 1 and 2. Based on the daily medians pooled for all subjects, the regression results are as follows. Experiment 1: fixed conditions ($T = 2$ and 10 s) $t = 0.29T + 0.75$, $r^2 = 0.38$, $n = 55$. Experiment 2: fixed conditions

Fig. 4. Waiting time, t , in red, as a function of food delay, T , in green for the four clamped, two fixed, and two dependent conditions in Experiment 2. The individual birds are denoted by small letters (a, b, c, and d); the points are medians of daily medians, averaged across all exposures to a condition (first 10 intervals each day excluded). The conditions are indicated by the arrangement of the individual data points: vertically (fixed), along a hyperbola (dependent), or along a straight line of negative slope (clamped). The straight lines connect the averages for the three conditions.

($T = 6$ and 14 s) $t = 0.44T - 0.64$, $r^2 = 0.62$, $n = 74$. The probability level for the difference between the r values is $p = .057$ (i.e., just short of conventional significance). In all individual cases the gradient is steeper in the second experiment than in the first; in all but one case (Bird 280) the intercepts are lower in the second experiment than in the first.

Controlling Events: Timing or Delay of Reinforcement?

What determines waiting time, t ? It seems clear that the rule (contingency) relating food delay, T , to t has no effect beyond the actual delays involved, because all the average waiting times lie on the same t versus T function, irrespective of the contingency relating T to t . Hence, the time of food delivery itself must be the critical factor. But we can distinguish two possible ways for this time to act: (a) via peck $\rightarrow$ food delay (i.e., delay of reinforcement), which implies that T (the delay time in green) alone is the controlling variable and t is simply a measure of response strength, analogous to a latency; (b) via interfood in-

Table 3

Coefficient of variation of waiting time for the clamped and fixed conditions in Experiment 2.

Condition	Bird 15	Bird 20	Bird 195	Bird 280
Clamped 3 s	0.57	1.23	0.85	0.72
Clamped 8 s	0.72	0.70	0.80	1.02
Clamped 13 s	0.58	0.81	0.50	0.62
Clamped 18 s	0.52	1.28	0.71	0.48
<i>M</i> clamped	0.60	1.01	0.71	0.71
Fixed 6 s	0.65	0.81	0.72	0.59
Fixed 14 s	0.60	1.19	0.70	1.02
<i>M</i> fixed	0.62	1.00	0.71	0.80

terval (i.e., the expected or typical time of food delivery), which implies a timing process for which $t + T$ is the critical variable.

It is not possible to discriminate between these possibilities without making some assumption about how T , or $t + T$, affects waiting time. If the effect is relatively local (e.g., T in cycle N is the major determiner of t in the following cycle, $N + 1$), the two possibilities can be distinguished in the following way: If food delay, T , is the driving factor, then the variability (appropriately scaled) in t , the dependent variable, should be least in conditions in which the putative independent variable, T , is constant; that is, in the fixed conditions. Conversely, if interfood time, $t + T$, is the real independent variable, the variability of t should be least in the condition with constant $t + T$; that is, in the clamped conditions. If the effect of typical food delay is not local, but represents some kind of average across many interfood intervals, then this comparison may fail to discriminate between the two processes, because average interfood interval even in the fixed condition may well vary little.

It is well established that the standard deviation of waiting-time distributions is roughly proportional to the mean (e.g., Gibbon, 1977). Hence, the variability of waiting-time distributions with different means can be compared by looking at the coefficient of variation (CoV), the standard deviation divided by the mean, for each distribution. This comparison is made for all 4 birds, and the four clamped and two fixed conditions, in Table 3. It is clear without any need for statistics that there is no significant difference in the coefficient of variation for the waiting-time distributions under these two procedures.

Comparison of CoV for the fixed and

Fig. 5. Normalized waiting-time distributions. Relative-frequency (equal-area) distributions of waiting time, $\log t$, for every session under each of the six conditions of Experiment 2 for Bird 15. Distributions have been shifted along the $\log t$ axis so that their maxima coincide. See text for details.

clamped conditions fails to show any difference, which implies either that the effect of T (or $T + t$) is not local, but extends over several cycles, or that both T and $T + t$ have some effect. We have not been able to devise an analysis to settle this issue conclusively. If T is the major factor, however, then waiting time should have the character of a latency—a “strength” measure—which implies (for many, if not all, latency models) that t should be distributed exponentially (i.e., as the output of a random process), or at least not unimodally, as might be expected of the output of a timing process.

To test this argument, and to provide an additional comparison between the variability of t under the fixed and clamped conditions, we derived normalized waiting-time distributions for both conditions as follows. The individual t values for a given condition (procedure and parameter value) were log-transformed, which, according to the scalar-timing assumption, should produce symmetrical distributions with similar variance for all mean t values. This procedure yielded six equal-area distributions for each pigeon. These six distributions were then shifted along the $\log t$ axis so that their modes coincided, which allows us to compare variabilities directly. The resulting normalized distributions are shown in Figure 5 for Bird 15, which was typical.

Fig. 6. Average cumulative records of responding in the red stimulus for all sessions under the fixed condition with $T = 6$ or 14 s for all pigeons. The records were derived by averaging the times of occurrence of the first, second, etc., responses following stimulus onset (the occasional reversals late in some records are artifacts caused by variation in the number of responses at high response counts).

The distributions were in every case unimodal and symmetrical, as expected from a timing process. The distributions from the two fixed conditions are generally somewhat broader than the average for the clamped conditions, although the differences are very small and not statistically significant.

Pecking in Green

Pecks on the green key had no scheduled effect. Nevertheless, the resemblance between our procedure and that for autoshaping led us

to expect that the animals would peck, and they did. In most cases, the pecks followed an accelerating FI-like pattern. Figure 6 shows averaged cumulative records for typical sessions for all 4 pigeons under the two fixed conditions.

In autoshaping experiments in which the intertrial interval (ITI; analogous to t in these experiments) is varied and the prefood-stimulus duration (analogous to T) is held constant, there is a direct relation between ITI and speed of acquisition of the autoshaped response (e.g., Gibbon & Balsam, 1981). We looked to see if in our experiments peck rate in the prefood stimulus had a similar relation to waiting time, but it did not. Table 4 shows the regression relation and r^2 value for the two typical birds in the two fixed conditions (we looked only at the fixed conditions, because only in these conditions is the time available for pecks in green constant for all t values). In no case was there was a significant relation between number of pecks in green and the preceding waiting time.

DISCUSSION

The results of Experiment 2 confirmed and extended those of Experiment 1: The relation between waiting time and food delay (or interfood interval) was approximately linear, more or less independently of the contingency relating food delay to waiting time. Pigeons in these experiments were unable to adjust their waiting times to conform to the optimal value and were constrained to behave according to the linear-waiting process.

The slope of the linear-waiting function was steeper in Experiment 2 than in Experiment 1, but this result seems to be explained not so much by long-term changes in performance as by a low-end plateau at $t = 0.5$ s for $T < 4$ s, which affected Experiment 1 (in which the lower T value was 2 s) more than Experiment 2 (in which the lower T value was 6 s).

We found no correlation between waiting

Table 4
Regression relation between waiting time and subsequent number of pecks in red for the two fixed conditions in Experiment 2.

Bird 20	fixed 6 s	$Y = -0.10X + 4.22, r^2 = -.11, n = 600$
	fixed 14 s	$Y = 0.01X + 15.36, r^2 = .02, n = 600$
Bird 195	fixed 6 s	$Y = -0.11X + 5.17, r^2 = -.14, n = 702$
	fixed 14 s	$Y = -0.13X + 8.61, r^2 = -.18, n = 800$

time in the presence of the red stimulus and number of pecks in the subsequent green stimulus, even though such a correlation is implied by the data of Gibbon and Balsam (1981) on speed of acquisition in autoshaping. The most likely reason is that Gibbon and Balsam controlled the waiting time (intertrial interval), whereas in our experiments waiting time was under the control of the pigeon. (There is, perhaps, an analogy to the correlation between meal size and the preceding intermeal interval, which in rats is negligible under free-feeding conditions, but easily can be made large and positive by enforcing long intermeal intervals; cf. Staddon, in press.)

We were not able to distinguish between the two possible candidates for the controlling variable in these experiments (T or $T + t$), although the waiting-time distributions were in every case symmetrical and unimodal—implying a timing process rather than a latency—which favors interfood interval. But notice that a delay-of-reward interpretation equivalent to a given timing interpretation can always be found. For example, suppose the bird sets waiting time equal to the preceding reward delay: $t_N = T_{N-1}$; then in the clamped condition, where $T_N = C - t_N$, $t_N = C - t_{N-1}$, which is a process that stabilizes at $t = C/2$ —the same prediction as a timing process that sets t equal to half the interfood interval. A delay-of-reward process that sets t as a linear function of the preceding reward delay will always make the same mean-value prediction as one that sets t as a linear function of the preceding interfood interval. Hence, the timing and delay-of-reinforcement interpretations are not distinguishable by looking at mean t values.

The waiting-time distributions in the clamped conditions were not significantly less variable than those in the fixed condition, as they should have been if t were a function of the preceding interfood interval. This implies either that both T and $T + t$ have an effect or that waiting time in interval N is a function of more than just the preceding interfood interval. But if waiting time in interval N depends upon several preceding interfood intervals, performance should change slowly from one schedule-parameter value to another. Unfortunately, we found almost no evidence for slow, progressive changes from one condition to the next. Variability was admittedly high, which would tend to obscure small, gradual

changes; nevertheless, the birds seemed to reach new equilibria within a single session. Note that the slope of the linear-waiting line was higher in the second experiment (in which conditions changed daily) than in the first (when they changed only after several days). This implies that timing was at least as good in the second experiment as in the first. We tackled the problem of dynamics directly, by a different method, in Experiment 3.

EXPERIMENT 3: TWO TESTS OF A QUASI-DYNAMIC MODEL OF WAITING

Experiments 1 and 2 showed that pigeons will set their waiting time, t , as an approximately linear function of the typical time to food, $t + T$, under a wide variety of conditions. Moreover, they seem to do this quite quickly, because the slope of the function relating t to $t + T$ was just as steep when conditions changed daily as when conditions changed only after several days.

The equilibrium properties of this linear-waiting process can be predicted from the following model, which relates waiting time in cycle $N + 1$ to the preceding interfood interval (or food delay, because the two are formally indistinguishable, as noted above). If we denote typical food delay (interfood interval) by E (to indicate that it represents an expectation based upon past experience of food delays), and waiting time by t , and assume that the animal alters t so that it conforms to a linear function of E with fixed parameters, then perhaps the simplest assumption we can make is that the change in t from cycle to cycle will be a positive function of the difference between the actual value of t and the linear relation, $t = AE + B$, observed at asymptote: If t is less than predicted by the asymptotic relation, then it should increase; if t is greater than the linear relation, it should decrease. Formally, the change in t is given by

$$\Delta t = G[(AE + B) - t], \quad (1)$$

where G is some positive function and A and B are positive constants (B is usually small). Function G is of course unknown, but if we assume that it is simply a positive multiplier (which may even vary from cycle to cycle) then Equation 1 can be used to derive the equilibrium properties of the process, even though we

Fig. 7. Cobweb waiting model: fixed schedule. Control function shows how waiting time (t_N) depends upon the preceding interfood interval ($E = t_{N-1} + T_{N-1}$). Schedule function shows how the interfood interval, $t_N + T_N$, depends upon the current waiting time, t_N . In this case, $T = \text{constant}$ (i.e., there is no dependency; see text for details).

remain ignorant about such dynamic properties as the learning curve (i.e., the precise magnitude of changes in t from cycle to cycle) and the number of cycles necessary to achieve equilibrium. Staddon (1988) has termed this kind of model *quasi-dynamic* because it represents a dynamic process, but because the multiplier G is not defined, can be used only to derive equilibria, not time-paths (which precludes any direct dynamic test). The quasi-dynamic version of Equation 1 is then

$$\text{delta}(t) = (AE + B) - t_{N-1}, \quad (2)$$

where t_{N-1} is the waiting time in cycle $N - 1$ and $\text{delta}(t)$ is the expected change in t . Equation 2 is linear in t_{N-1} over time periods when E is constant. At equilibrium (which is always stable, because Equation 2 has a negative slope), $\text{delta}(t) = 0$, hence

$$\hat{t} = AE + B, \quad (3)$$

which is simply the empirical relation, given that $E = t + T$ (i.e., the expected food delay is equal to the actual average food delay).

Suppose we now arrange the actual food delay (interfood interval) in cycle N to be a function of waiting time in cycle N , as we did in Experiments 1 and 2. If the expected food delay on the N th cycle is equal to the actual food delay on the preceding cycle, then

$$E_N = t_{N-1} + T_{N-1}, \quad (4)$$

which implies for the fixed conditions, $E_N = t_{N-1} + T$, because T is constant. Substituting in Equation 2 yields

$$\text{delta}(t) = [A(t_{N-1} + T) + B] - t_{N-1}, \quad (5)$$

which has a stable equilibrium (when $\text{delta}(t) = 0$) at

$$\hat{t} = A(t + T) + B,$$

which is the same empirical relation as before. The same solution can be derived for the clamped and dependent conditions. Hence, the quasi-dynamic model embodied in Equations 2 and 4 is consistent with what we found in Experiments 1 and 2, namely that the relation set by the animal between t and T is independent of the rule set by the experimenter relating T_N and t_N .

This analysis, which in its essentials is very simple, is perhaps easier to follow in the graphical form shown in Figure 7. The figure shows the empirical relation between E (i.e., interfood interval) and waiting time, t (Equation 3: the line of positive slope labeled Control Function) and the constraints imposed by the fixed condition (labeled Schedule Function: fixed). The "cobweb" line shows the t values in successive cycles of the procedure, beginning with t_0 (this cobweb idea is an old one in economics; see Hursh, 1980). It is clear that for these two functions the cobweb process converges, yielding equilibrium points along the control function. The other two schedules in Experiments 1 and 2, the clamped (for which the schedule function is a vertical line: $E = \text{constant}$) and the dependent (schedule function: $E = t + K/(t + 1)$), also yield stable equilibria along the control function. Note that in order to draw these cobweb illustrations it was necessary to make the simplifying assumption that G in Equation 1 equals 1, an assumption not made by the quasi-dynamic analysis.

In Experiment 3 we studied a class of autocatalytic schedules for which this model yields unstable solutions. The graphical analysis for a divergent autocatalytic schedule is shown in Figure 8. The control function is as before, but there is a new schedule function of the form $T = wt$ (food delay directly proportional to waiting time), which, if $E = t + T$, implies

$$t + T = E = t(1 + w). \quad (6)$$

Substituting Equation 6 in Equation 2 (and omitting subscripts for readability) yields

$$\text{delta}(t) = (At(1 + w) + B) - t,$$

which simplifies to

$$\text{delta}(t) = B - t[1 - A(1 + w)]. \quad (7)$$

If $A(1 + w) > 1$, which implies that $w > 1/A - 1$, then $\text{delta}(t)$ is always positive, which means that t should increase without limit. (Notice that this a *positive feedback* procedure, because the slope of the $\text{delta}(t)$, versus t function is positive.) This divergent case is illustrated in Figure 8. Conversely, if $w < 1/A - 1$, Equation 7 has a negative slope and $t = B/[1 - A(1 + w)]$, a very small value.

From Experiments 1 and 2 we established that A is in the region of 0.2 to 0.5; hence a value of $w > 4$ should yield the divergent pattern, whereas a value of $w < 1$ should yield the convergent pattern. We looked at our pigeons' performance under five such schedules in Experiment 3.

METHOD

Subjects and apparatus were the same as in Experiments 1 and 2.

Procedure

The same red/green cyclic procedure was used as in Experiments 1 and 2, but we used a different rule to determine T , time in green. We studied an autocatalytic schedule in which T was directly proportional to waiting time in red: $T = wt$. We looked at five values for w : 7, 4, 1, $\frac{1}{4}$, and $\frac{1}{7}$. The w value was changed every day or two according to the sequence shown in Figure 9, which also shows the waiting times in each cycle of each experimental session. Sessions lasted for 100 cycles or 90 min, whichever came first.

RESULTS AND DISCUSSION

Figure 9 shows waiting times for each pigeon during the entire course of Experiment 3. We considered five w values: 4 and 7 (labeled A and B) were expected to lead to divergent behavior (increasing t value); 1, $\frac{1}{4}$, and $\frac{1}{7}$ (labeled c, d, and e) to convergent behavior (decreasing t value). It is clear that the parameter value makes a big difference to performance: In every case, when w was 1, $\frac{1}{4}$, or $\frac{1}{7}$, waiting times were very short. When w was

Fig. 8. Cobweb waiting model: autocatalytic schedule. Functions defined as in Figure 7. Because the schedule function lies below the control function and has a lower slope, waiting time increases without limit from cycle to cycle.

4 or 7, waiting times were longer, but the pigeons usually did not cease to respond completely (although 3 of the 4 birds extinguished, by our 90-min criterion, at least once). Nevertheless, when behavior followed the divergent pattern (most of the sessions labeled A or B) the "runaway" autocatalytic quality of the behavior was quite apparent.

It seems clear from the data in Figure 9 that the feedback properties of the schedule had an effect along the lines predicted from our quasidynamic model. When the schedule "gain," w , was 1 or less the pigeons waited only a very short time (on the order of 1 s) before responding, whereas when w was 4 or more, they waited up to 30 s on schedules where responding after 1 s would have produced food after no more than 4 or 7 s.

Nevertheless, pigeons' responding rarely extinguished, even with high w values; this implies some error or omission in our model. The most likely candidate is the assumption of Equation 4 that the expected time to food, E , is a function solely of the preceding interfood interval. Although the data from Experiments 1 and 2 strongly suggest that pigeons adapt rapidly to changes in interfood interval, there is also much evidence that their behavior can come under the control of interfood intervals more than one previously. For example, Innis and Staddon (1971) showed that pigeons can

Fig. 9. Individual waiting times during each cycle of each condition in Experiment 3. Letters denote the w value in effect as follows: $w = 7$ (A), 4 (B), 1 (c), $\frac{1}{2}$ (d), $\frac{1}{4}$ (e). Because typical waits were about $0.3T$, the one-back model predicts that $w > 3.5$ (A, B) results in divergence, $w < 3.5$ (c through e) results in convergence.

track cyclically varying interfood intervals, implying control by at least the preceding two intervals; the fact of transfer from 1 day to the next in the usual "blocked" procedure implies an effect of even more remote intervals. It is easy to see that an effect on the waiting time of interfood intervals earlier than the preceding one tends to stabilize the timing process and mitigate the runaway patterns predicted by our one-back model.

GENERAL DISCUSSION

The properties of temporal control have been studied mainly from the viewpoints of psychophysics, psychophysiology, and stimulus control. For example, the standard deviation of waiting distributions on fixed-interval schedules is usually proportional to the mean, implying a scalar-timing property for temporal discrimination (e.g., Catania, 1970; Gibbon, 1977; Stubbs, 1980). The mean and variance of the waiting distribution in the so-called peak procedure of Roberts, Church, and their associates are thought to represent the properties of an internal clock (e.g., Gibbon, Church, & Meck, 1984). Animals come to respond when the clock "setting" reaches a certain value dependent on the typical time for food delivery, and the apparent rate of the clock can be altered by motivational and pharmacological manipulations. Finally, the role of food and other "time markers" on periodic schedules has been studied as an example of inhibitory or excitatory (temporal) stimulus control, with some markers (e.g., food) capable of controlling long waiting times and others (e.g., colored lights) capable of controlling only brief waits (e.g., Staddon, 1974; Staddon & Innis, 1969).

The present experiments were motivated by a different issue: the distinction between obligatory versus facultative behavioral mechanisms. This is a distinction that has not always been drawn clearly in the past; it was not always recognized that demonstrating the existence of a mechanism—temporal discrimination, for example—under one set of conditions does not imply that those conditions will always produce the same result, or that this mechanism will necessarily operate under other conditions. The distinction is like that between a law and a policy (or strategy). Natural law is inviolate and omnipresent; it operates al-

ways, and under all conditions. But a policy is a rule that can be changed depending on circumstances. Much human behavior is best described as a set of policies. On fixed-interval schedules, for example, people can show temporal discrimination, but they sometimes show quite different (and often less optimal) patterns (see Lowe, 1979). In decision-making tasks, people sometimes follow optimal policies and sometimes follow simple rules that are suboptimal (e.g., Kahneman & Tversky, 1986); there are many other examples.

Because pigeons and rats behave in less complex ways than people do, there has been a temptation to consider their behavior less flexible, more obligatory and less facultative, than human behavior. Indeed, our experiments have extended the range of situations in which linear waiting is an obligatory process in pigeons. Good adaptation to spaced-responding schedules (which implies a waiting function with a substantially higher slope than ours) suggests that the process may be supplanted or modified when the contingencies are severe, however. Nevertheless, under less severe conditions, it seems that linear waiting will always operate, with implications for reinforcement-schedule performance that remain to be worked out in detail.

That pigeons long trained on periodic-food schedules will wait an approximately constant fraction of the typical interfood interval before responding has been known for many years (see Catania, 1970; Ferster & Skinner, 1957; Richelle & Lejeune, 1980). Our experiments have added to this knowledge in two ways; first, by showing that the process seems to operate identically under three quite different food-delay schedules we have increased support for the hypothesis that the linear-waiting process is an obligatory one. Second, by producing unstable behavior under a one-back autocatalytic schedule, we have shown that the preceding interfood interval (or food delay) makes a major (but not always decisive) contribution to waiting time in the next interval. Questions remaining to be answered include the causal details: What earlier time intervals (food delays or interfood intervals) contribute to current waiting time, and how do the effects of previous intervals act in combination? What is the relative importance of interfood interval and response-reward delay as determiners of waiting time? These experiments do not dis-

tinguish between them, and our equations have the same form whether written in terms of t_N and $E (=t + T)$ or t and T .

It may be worth noting that the linear-waiting process is a highly adaptive one under natural conditions. If food is simply periodic, for example, it makes great adaptive sense to devote the early postfood period to activities other than food-related ones (see Staddon & Simmelhag, 1971; Timberlake & Lucas, 1985). Given the importance of the rates at which activities (e.g., eating, metabolism) occur, it also makes sense that the waiting time should be roughly proportional to the typical interfood interval, because then both food-related (terminal) and non-food-related (interim) activities occur at approximately constant rates.

On the other hand, if food occurs on some kind of ratio schedule, a process that causes the animal to wait a relatively small fraction of the typical food delay (i.e., a process that acts in anticipation of food, rather than one that produces behavior that coincides with the expected time of food delivery: parameter $A < 1$ in Equation 1) will, by the positive-feedback process described in the introduction to Experiment 3, after a few iterations cause food to be procured almost as rapidly as possible. (Food delay will be limited by the minimum time necessary to emit the terminal ratio, similar to the delay period, T , in our experiments. This is the source of the well-known fixed-ratio postreinforcement pause.)

The linear-waiting process fails only when response to food delay depends on waiting time, as it did in these experiments. But in natural environments food delay never depends on waiting time, so that a mechanism vulnerable to such a contingency will not be selected against.

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