*INCOME MAXIMIZING IN CONCURRENT
INTERVAL-RATIO SCHEDULES*

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Three mice chose between concurrent variable-ratio variable-interval schedules to produce a warm air stream while they were housed in a cold chamber. Across conditions, the duration of the warm air stream was varied between 10 and 80 s and was equal for both schedules. Preference for the VI schedule covaried with reinforcer duration as predicted by maximizing accounts of choice.

Key words: economics, concurrent variable-ratio variable-interval schedules, maximizing, heat reinforcer, bar press, mice

When choosing between variable-ratio (VR) and variable-interval (VI) schedules, an animal can maximize its reinforcement in a session of fixed duration by responding mostly to the VR and switching occasionally to make a single response to the VI. Such a strategy takes advantage of an essential difference between these schedules' feedback functions: Over a wide range of schedule values and response rates, marginal increases in responding on VRs produce more reinforcement than do marginal increases in VI response rates. Hence, in most circumstances choosing a VR more frequently than a VI is consistent with maximizing the rate of reinforcement.

Herrnstein and Heyman (1979) tested whether pigeons follow such a maximizing strategy on concurrent VR VI schedules. Using different VR-VI schedule pairs, they found that pigeons often responded more to the VI than the VR, even though such choice allocation failed to maximize the local rate of re-

inforcement. They concluded that choice in this circumstance is not controlled by a rate-maximizing response rule. Moreover, because the relation between VR/VI choice and reinforcement ratios was well described by the generalized matching equation (Baum, 1979), they interpreted their results as establishing the primacy of matching over rate maximizing in choice.

Although we agree with Herrnstein and Heyman's (1979) conclusion that pigeons often do not choose so as to maximize their rates of food reinforcement, we caution that the predictive inadequacy of this particular maximizing account need not extend to alternative maximizing formulations. In fact, we propose in this report that optimality rules do govern choice; however, the dimension of food reinforcement optimized is not the rate of reinforcement per session, but the number of reinforcements earned per day (income maximizing).

This thesis could not be tested in the Herrnstein and Heyman (1979) study because they kept daily food income constant. They achieved this outcome in two ways: by ending sessions after 60 reinforcers and by maintaining body weights at 80% of free-feeding levels. Had they ended sessions on the basis of time (e.g., after 60 min) and required animals to earn their total food ration during these sessions, then total food intake would have varied as a function of choice. These changes would have transformed their experiment into an *income-maximizing* test, because the response rule that maximizes the reinforcement rate on concurrent VR VI schedules would also maximize an animal's daily income.

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We entertained replicating the Herrnstein and Heyman (1979) study with the changes mentioned above, but we were troubled about using food as a reinforcer. The problem we foresaw was that an animal might substitute its body fat for food earned in a session. As a consequence of the slow depletion rate of body fat, an animal could opt to maximize leisure rather than food intake in a session, replacing caloric deficits produced from its fat deposits.

One solution to this problem is to use a reinforcer that is not readily stored in the body. With such a good, an animal has a more limited capacity to substitute body stores for earned reinforcement, and will therefore be more likely to maximize income by adopting an income-maximizing response rule. On the assumption that heat in a cold environment qualifies as such a nonstorable reinforcer, we exposed mice to concurrent VR VI schedules in which their choices occasionally produced a warm air stream while they were situated in a cold chamber.

We altered the duration of the heat reinforcer across conditions but kept its value the same for both schedules. A common finding when heat duration is manipulated is that animals defend body temperature by responding at high rates when heat durations are short and at low rates when heat durations are long (e.g., Baldwin, 1968; Carlisle, 1966; Matthews, 1971; Weiss & Laties, 1960).

This relationship between reinforcer duration and response rate, when coupled with the differences between VI and VR feedback functions noted above, permits a simple test of optimality accounts of choice. When heat durations are increased animals should increase their preference for the VI schedule. This prediction follows from the fact that body temperature can now be defended with lower reinforcement rates. How are response rates affected? By virtue of their feedback functions, response-rate decreases on the VI produce greater decreases in reinforcement rates than do VR response-rate decreases. Thus, VR response rates should decrease. In other words, response cost is minimized by decreasing the VR response rate relative to the VI rate when heat durations are increased. Conversely, when reinforcer durations are shortened, response rates will increase in defense of body temperature. Because of feedback-function differences, these additional bar presses are more

efficiently expended on the VR than the VI schedule. Consequently an increased preference for the VR is predicted.

METHOD

Subjects

Three experimentally naive adult male mice (M91, M92, and M94), provided by Charles River Laboratories (Strain C3H), served as subjects. They had unrestricted access to food and water in their home cages.

Apparatus

The experimental space consisted of a Plexiglas cylinder (15 cm high, 11 cm wide), open at its ends, that sat vertically on a wire-mesh floor, and two response levers that protruded 2 cm into the cylinder. These levers were 1 cm above the floor and were spaced 5 cm apart. A strip of aluminum (1 by 3 cm) that was perpendicular to the arm of the microswitch (Cherry Electric #E22) served as the response surface. A force of approximately 1 N was sufficient to activate each microswitch.

A Plexiglas cylinder (24 by 20.5 cm) surrounded the smaller cylinder. Two 24-Vdc bulbs that provided general illumination were embedded in the outer cylinder, 15 cm off the floor and 15 cm apart, behind the response levers. This cylinder was connected to an air inlet tube by a conical ceiling. The air inlet tube provided a 27 km/hr air stream at either of two temperatures: 3 or 37 °C. The convective thermal controller that produced these temperatures (Matthews, 1969) could switch between these cold and warm streams in 1 to 2 s.

Procedure

Before beginning the experiment, each animal was exposed continuously to the cold air stream and was trained by the method of successive approximations to respond to each of the two levers for a 10-s presentation of the warm air stream. Once reliable responding was obtained, animals were exposed to the choice contingency. In the first session of this procedure, animals chose between independent VR 2 and VI 2-s schedules, each of which was assigned to a separate lever. A changeover delay ensured that a reinforcer assigned to a lever would be delivered only for a response that follows a changeover by at least 1.5 s (Herrnstein, 1961). During the next 20 ses-

Table 1

Order of procedures and data for each subject. Data represent means of final five 30-min sessions on each condition.

Subject	Condition	Lever with		Rein- forcer duration (s)	Responses		Time (s)		Reinforcers		Change- overs
		VR	VI		VR	VI	VR	VI	VR	VI	
M91	1	left	right	10	483.6	90.6	1,566.4	233.6	85.4	5.4	31
	2			20	526	115.4	1,479.4	320.6	96.2	11.8	68.2
	3			40	376.8	190.2	1,303.4	496.6	59.8	13.2	80.8
	4			10	645	39.2	1,686.8	113.2	127.4	4.8	30.2
	5 ^a			10	399.6	88.2	1,520.2	279.8	35.6	4.8	37
	6 ^a			40	467.2	166.6	1,323.4	476.6	42.2	7	70.6
	7 ^a			10	414.6	111.6	1,069.2	730.8	40.4	8.2	38
	8			10	651.4	45	1,519.2	280.8	122.8	5.2	32.2
M92	1	left	right	10	287.6	156.8	1,274.8	525.2	39.2	9.2	79.2
	2			20	394.2	105.6	1,307.6	492.4	65.6	11.8	72.6
	3			40	318.8	169.2	1,123	667	44.2	11.8	87.8
	4			10	514	105	1,418.8	381.2	88.2	8	62.2
	5			40	300.6	182.4	1,047.6	752.4	39.6	11.6	94.2
	6			80	128.4	142	691.4	1,108.6	13.6	12.8	73.2
	7			10	510.4	154.4	1,273.6	526.4	81.4	12.6	90
	8			40	373.4	147.6	1,265	535	52.2	11.8	88
M94	1	right	left	10	379	142.4	1,139	661	67	11.8	65.8
	2			40	189.4	171.2	820.8	979.2	20.6	16.4	79
	3			10	277.2	79	1,471	329	48	10.4	35.4
	4			40	221	134.2	1,288.4	511.6	35.8	11.8	62.4
	5			10	214	29.8	1,588	212	40.4	4.6	15.8

^a Concurrent VR 10 VI 180-s schedules. All other conditions VR 5 VI 90-s schedules.

sions, the size of each schedule was increased gradually, care being taken that schedule changes did not result in exclusive preference for one schedule. After this preliminary training, a terminal schedule pair (VR 5 vs. VI 90 s) was chosen for all subjects. These schedules were used throughout the experiment, except for three conditions with M91 in which choice was between VR 10 and VI 180-s schedules.

The heat reinforcer lasted 10, 20, 40, or 80 s, depending on the condition. Each daily session lasted 30 min, and each condition lasted 25 sessions. Except where noted, all data are based on the means of a given measure during the last five sessions of a condition. The order of experimental conditions for each mouse is presented in Table 1.

RESULTS

In addition to listing the order of procedures, Table 1 presents for each subject in each condition the mean number of responses, reinforcers, and changeovers per session. Two features of these data are noteworthy. First, at the values chosen, animals tended to respond more to

the VR than to the VI schedule. Second, the response rates were lower than those typically seen with food-reinforced behavior.

Figure 1 presents for each subject the proportion of responding, time allocation, and reinforcement that occurred to the VI schedule during each condition of the experiment. Conditions are presented in their order of occurrence on the *x* axis and are identified by the duration of the heat reinforcer during that condition. As noted in the top panel, M91 chose between VI 180-s VR 10 schedules for three conditions.

In 16 of 18 comparisons, preference for the VI, whether measured by response or time allocation, covaried with reinforcer duration—that is, increases and decreases in reinforcer duration resulted, respectively, in increases and decreases in preference for the VI schedule. One exception to this outcome occurred in the transition from a 40-s to a 10-s reinforcer duration for M91 when exposed to concurrent VI 180-s VR 10 schedules. For this subject, the change in relative response rate did covary with the change in reinforcer duration; however, relative time allocation moved in the op-

Fig. 1. Relative rate of VI response, VI time allocation, and VI reinforcement for each reinforcer-duration condition for each of 3 subjects.

posite direction. The second exception can be found in comparing the first versus the second condition for M92. Despite the increase in reinforcer duration from 10 to 20 s, VI preference and VI reinforcement frequency decreased with this increase in reinforcer duration.

Figure 2 reorganizes the data from Figure 1 so that it is possible to see for each subject the functional relation between reinforcer duration and the relative rate of VI responding, time allocation, and reinforcement. The closed circles represent M91's data when choice was between concurrent VI 180-s VR 10 schedules. All other performances are based on concurrent VI 90-s VR 5 schedules. Within each

panel are lines of best fit that indicate the trend of the relationship between reinforcer duration and the three relative VI measures.

In terms of relative response rates, all slopes are positive, indicating that this measure of VI preference increased consistently as reinforcer duration increased. This covariation was also apparent in the best-fit functions for relative time allocation and relative reinforcement rate. The only exceptions were the time and reinforcement data of M91 during concurrent VI 180-s VR 10 schedules.

DISCUSSION

In this experiment, mice were placed in a cold chamber where they chose between concurrent VR VI schedules that provided access to a warm air stream for 10, 20, 40, or 80 s, depending on the condition. A prerequisite for assessing the relation between reinforcer duration and choice was to choose values of each schedule that were likely to ensure concurrent responding. We saw in a pilot study that mice respond at low rates for heat reinforcement and that the maintenance of responding to the VR required that it be unusually rich, both absolutely and relative to the VI schedule used. This use of a rich VR schedule may account for a difference between Herrnstein and Heyman's (1979) results and ours: We found that mice typically responded more to the VR than the VI, whereas in several of Herrnstein and Heyman's conditions, pigeons chose the VI more than the VR.

As shown in Figures 1 and 2, preference for the VI schedule covaried with reinforcer duration in this study. An optimality explanation of this result assumes that animals chose just frequently enough to defend their body heat. Their optimizing calculation involved determining the rate and locus of choice that was most efficient in producing the desired rate of reinforcement.

This calculation could have occurred at either a molecular or molar level. Defined molecularly, animals respond so as to maximize the relation between probability of reinforcement and a response. Molar income maximizing involves optimizing the relation between response rates to both schedules and the rates of reinforcement those schedules provide. In the discussion that follows, we will explain

income maximizing in molar terms even though future work may determine that income maximizing actually operates at a more molecular level.

When low response rates are sufficient for an animal to meet its heat requirements—a circumstance produced by having long reinforcer durations—all choices should be to the VI. This prediction follows from the fact that the low response rates produce higher local rates of reinforcement from VIs than from VRs. However, when reinforcer durations are short, animals must increase their response rates to defend their body temperatures. At some point, marginal increases in VI responding are less productive of reinforcement than is responding to the VR schedule. When reinforcer durations decrease below this level, an animal should emit all *additional* responses to the VR.

This optimality interpretation argues that choice is stratified as a function of the response rate needed to keep the animal warm. Attendance to this optimality rule on concurrent VR VI schedules would produce as a byproduct the covariation between reinforcer duration and VI preference seen in Figures 1 and 2. Nevertheless, if our account is correct, these relative-rate plots are a consequence of choice stratification and not an index of it. To test stratification directly, we need to see how absolute rates of responding to the VI and the VR changed as a function of reinforcer duration.

Toward this end, we plot in Figure 3 the mean change for each schedule in each subject's responses per session from the mean levels seen during the 10-s reinforcer conditions. Because VR responding was present for all subjects during the 10-s reinforcer conditions, a stratification account predicts that increases in reinforcer duration should reduce the level of VR responding; and as long as some VR responding persists, VI behavior should remain unchanged.

The VR data in Figure 3 are consistent with a stratification interpretation in that these rates decrease monotonically with increases in reinforcer duration. The VI data are more difficult to interpret. During the 20-s and 80-s reinforcer conditions, rate changes were neither consistent between subjects nor large—an outcome compatible with our account. However, during the 40-s reinforcer conditions, VI response rates increased for all subjects. This

Fig. 2. Relative rate of VI response, VI time allocation and VI reinforcement as a function of reinforcer duration. See text for details.

result is not predicted by our stratification explanation.

Even if choice in this experiment cannot be explained solely in terms of income maximizing, it is clear that this account is compatible with major features of the choice and absolute rate effects obtained in this study. Moreover, income maximizing can explain why previous tests for the operation of maximizing processes on concurrent VR VI schedules have sometimes failed (see Heyman & Herrnstein, 1986, for a review). The problem has been that these experiments permitted animals to maximize their rates of reinforcement even though such maximizing had no impact on their aggregate food intake. To the degree that income maximizing governs choice, altering the procedures of these studies so that maximizing reinforce-

Fig. 3. Changes for each subject in the mean number of VI and VR responses from their respective levels during 10-s reinforcer-duration conditions. See text for details.

ment rate also maximizes food intake should reveal the operation of optimality principles on concurrent VR VI schedules.

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