

*MOLECULAR MAXIMIZING CHARACTERIZES CHOICE
ON VAUGHAN'S (1981) PROCEDURE*

ALAN SILBERBERG AND JOHN M. ZIRIAX

THE AMERICAN UNIVERSITY

Pigeons keypecked on a two-key procedure in which their choice ratios during one time period determined the reinforcement rates assigned to each key during the next period (Vaughan, 1981). During each of four phases, which differed in the reinforcement rates they provided for different choice ratios, the duration of these periods was four minutes, duplicating one condition from Vaughan's study. During the other four phases, these periods lasted six seconds. When these periods were long, the results were similar to Vaughan's and appeared compatible with melioration theory. But when these periods were short, the data were consistent with molecular maximizing (see Silberberg & Ziriax, 1982) and were incompatible with melioration, molar maximizing, and matching. In a simulation, *stat* birds following a molecular-maximizing algorithm responded on the short- and long-period conditions of this experiment. When the time periods lasted four minutes, the results were similar to Vaughan's and to the results of the four-minute conditions of this study; when the time periods lasted six seconds, the choice data were similar to the data from real subjects for the six-second conditions. Thus, a molecular-maximizing response rule generated choice data comparable to those from the short- and long-period conditions of this experiment. These data show that, among extant accounts, choice on the Vaughan procedure is most compatible with molecular maximizing.

Key words: maximizing, matching, melioration, choice, key peck, pigeons

When animals are given choices between two concurrently available variable-interval (VI) schedules, the proportion of their responses or time allocations on these schedules typically approximates the proportion of reinforcements these schedules deliver (e.g., see de Villiers, 1977). These so-called matching relations for responses and time can be respectively defined in the following equations:

$$\frac{P_1}{P_1 + P_2} = \frac{R_1}{R_1 + R_2}, \quad (1)$$

and

$$\frac{T_1}{T_1 + T_2} = \frac{R_1}{R_1 + R_2}, \quad (2)$$

where *P* and *T* refer to responses and time allocated to a schedule, *R* refers to reinforcement frequency, and the subscripts 1 and 2 distinguish between the two VI schedules.

This research was supported in part by NSF grant BNS-8309045 to The American University. Address reprint requests to John Ziriax, Department of Radiation Biology and Biophysics, University of Rochester Medical Center, Rochester, New York 14642.

When written in a generalized form (see Baum, 1979), the descriptive adequacy of these matching equations is generally accepted. Despite these successes, there are several accounts of why matching obtains. One theory — what we call matching theory — states that these equations may actually define the process of choice allocation. Accordingly, animals are posited to be directly sensitive to relative rates of reinforcement among alternatives and to allocate their time and responses as described by Equations 1 and 2. A second approach has been to view matching not as the process of choice allocation, but as the outcome of another process — that of maximizing the rate of reinforcement.

One type of maximizing, called molar maximizing, is based on the demonstration that the relative response rate that maximizes the reinforcement rate is usually close to the locus of matching (Rachlin, Green, Kagel, & Battalio, 1976). A second type of maximizing, called momentary maximizing, is based on the fact that matching is produced if from moment to moment, animals

select the VI schedule that is more likely to provide reinforcement (Shimp, 1966; Silberberg, Hamilton, Ziriaux, & Casey, 1978). However, we favor a third maximizing account called *molecular maximizing* (see Silberberg & Ziriaux, 1982). Molecular maximizing is based on the proposition that animals allocate the times they spend responding to the schedules, as opposed to the responses themselves, such that they maximize the reinforcement rates these interchangeover times (ICTs) produce (see Silberberg & Ziriaux, 1982). This strategy, like Shimp's response-based momentary-maximizing account, produces matching on concurrent VI VI schedules.

Recently, Vaughan (1981; see also Herrnstein & Vaughan, 1980) advanced yet another account of the matching phenomenon, called melioration. According to this account, animals are sensitive to the local rates of reinforcement for each alternative (R_1/T_1 vs. R_2/T_2). If the local reinforcement rates differ, animals allocate more time to the richer alternative until the local reinforcement rates are equal. Melioration is defined by the equation:

$$R_D = R_1/T_1 - R_2/T_2. \quad (3)$$

When R_D is positive, more time is spent responding to VI₁, and when R_D is negative, preference shifts toward VI₂. Preference shifts continue until $R_D = 0$.

In order to distinguish among three of these accounts — those of molar maximizing, matching theory, and melioration — Vaughan created a new type of concurrent scheduling procedure. In this procedure, each of two computer-simulated VI schedules operated only when the animal responded to it (i.e., a timer ran only during 2 s following a relevant response). The combined times of the two schedules' operation cumulated in a single counter called the preference timer. When the preference timer reached 4 min, the relative time spent responding on the right key during that period was determined, and that relative time was used to define reinforcement rates for each schedule during the next 4-min period of responding.

When the relative right-key time was in the range of 0.125 to 0.25, both schedules provided 180 reinforcements/hour. Changes in time allocation from this range produced changes in reinforcement rate opposed to the direction of change. For example, if right-key relative time allocation increased to, say, 0.5, then right-key reinforcement rates dropped to 60/hour. Maintenance of such a relative time allocation, which would clearly violate the predictions of the matching equation, did not obtain. Instead, animals maintained their relative time allocations and relative response rates within the range of 0.125 to 0.25.

These results are consistent not only with matching theory, but also with melioration and molar maximizing. Therefore, of more interest in terms of distinguishing among accounts of choice is the outcome of Vaughan's second condition, described below, in which melioration and molar maximizing could predict different relative time allocations. In this condition, the right key provided: 180 reinforcements/hr when relative right-key time allocations were less than 0.5; a monotone-decreasing reinforcement rate (from 180 to 120/hr) as relative time allocation increased from 0.5 to 0.75; and 60 reinforcements/hr for relative right-key times greater than 0.75. On the left key, three different reinforcement rates were provided: 60/hr when right-key time allocations were between 0 and 0.125; 180/hr when relative time was between 0.125 and 0.25 and 0.875 and 1.0, and a monotone-decreasing rate of reinforcement (from 120/hr to 60/hr) as relative time allocation increased from 0.25 to 0.5.

With these choice contingencies, molar maximizing predicted relative right-key time allocations between 0.125 and 0.25, where the reinforcement rates for each key were 180/hour. This range was also consistent with the predictions of melioration theory since the expected difference in reinforcements/hour between keys equaled zero; however, if by chance time allocation varied from this range in the direction of greater right-key time allocation, a large difference in reinforcement rates (between 60/hour and

120/hour) ensued between schedules, such that increased right-key time allocation led to diminished left-key reinforcement. In such a situation, melioration could once again occur, but only at relative right-key time allocations between 0.75 and 0.875 where both keys provided 60 reinforcements/hour.

In the presence of these concurrent schedules, Vaughan found relative right-key time allocations shifted from the 0.125-0.25 range to the 0.75-0.875 range. Although these results are compatible with melioration, they are incompatible with molar maximizing, because in shifting their relative time allocations birds selected a lower reinforcement density (60/hour vs. 180/hour). As regards matching, steady-state relative time allocations in either aforementioned range produce matching. However, in the shift in relative time allocation from the left key to the right, animals endured substantial deviations from matching that would not have occurred had relative time allocations remained in the 0.125-0.25 range. For this reason, Vaughan argued against matching theory as the principle governing choice.

Although this study demonstrates inadequacies in a maximizing account of choice, the maximizing account tested is of the molar variety. Vaughan acknowledged this point, noting that his findings need not be viewed as inconsistent with optimization accounts, such as molecular or momentary maximizing, that emphasize control of choice by local or proximal factors. We carry his acknowledgment further by explaining why.

Molecular maximizing occurs when animals allocate their time to the momentarily better schedule as based upon each schedule's reinforcement probabilities over the next few seconds. Paradoxically, this emphasis on local reinforcement rates can lead a molecular-maximizing bird to an overall decrease in reinforcement rates in Vaughan's procedure. To illustrate, recall his second condition in which increases in relative right-key time allocations from the 0.125-0.25 range diminished left-key reinforcement during the next 4 min of responding. Countering this

diminution would require 4 min of greater time allocation to the left key despite its reduced reinforcement rate. Molecular maximizing based upon local between-key reinforcement rates would not produce this global maximizing. Instead of increasing left-key time allocations, a molecular maximizer should increase its right-key allocations in response to that key's momentarily higher reinforcement rate. When relative right-key allocations are in the range predicted by melioration (0.75-0.875), they should stabilize. Only in that range will the relative rate maximize local reinforcement probabilities, because shifts from this relative time-allocation range are met by shifts in local reinforcement rates opposed to the direction of change in choice allocation.

In this explanation of why molecular maximizing predicts Vaughan's results can be discerned the basis for distinguishing experimentally between this account, melioration, and matching theory. Molecular maximizing resulted in a preference for the right key in Condition 2 of Vaughan's study because the relative-rate calculation on which reinforcement rates were based was determined over the last 4 min of responding. This period is well beyond extant demonstrations of pigeon memory for prior choices and their consequences (e.g., see Shimp, 1981). Because a pigeon cannot maximize its choice allocations when it cannot recall these key events, a test of molecular maximizing requires the Vaughan procedure to be used with a preference timer of short duration so that choices and their outcomes can be recalled. With a short-duration preference timer, one can test the relative efficacy of each of these accounts by constructing schedules such that molecular maximizing and melioration make different predictions. For example, consider a schedule in which at relative right-key time allocations between 0 and 0.25 the left key provides 30 reinforcements/hour and the right key provides 240/hour; and at all other relative time allocations both keys provide 30 reinforcements/hour. With these concurrent schedules, molecular maximizing predicts

relative right-key time allocations less than 0.25 and melioration and matching theory predict relative time allocations greater than 0.25. If molecular maximizing controlled choice allocation in the Vaughan study, relative time allocations in the range predicted by melioration and matching theory should be evidenced with a 4-min preference timer, while with a short-duration timer, these allocations should be in the range predicted by molecular maximizing. These results would be consistent with our view that maximizing controls choice in the Vaughan procedure, but its operation is obscured by the use of a 4-min preference timer.

METHOD

Subjects

Four adult male White Carneaux pigeons (B1, B2, B3, B4), maintained at 80% of their free-feeding weights, served. All birds had extensive histories on concurrent-schedule procedures.

Apparatus

Four identical chambers, measuring internally 27.5 by 32.5 by 29 cm, each housed a single subject. With the exception of a stainless steel response panel and a wire-mesh floor, all internal surfaces were made of galvanized steel. The distances from the floor to the bottom of the 5.5 by 5-cm hopper aperture and the houselight were 5.5 and 26.2 cm, respectively. Three 2.54-cm diameter Lehigh Valley Electronics response keys, spaced 6.5 cm center to center, were located 21 cm above the floor. Each key operated at a minimum force of 0.15 N. The keys were transilluminated from behind the response panel by Industrial Electronics Engineers multistimulus projectors. A PDP-8/e minicomputer controlled all experimental events and data collection.

Procedure

Pigeons pecked on either of two concurrently lit keys (left key red, right key green). Reinforcement was arranged intermittently

for pecks on these keys, but depended on the way in which the birds allocated time between them. Time allocated to each key was measured in the following way. A peck started a 2-s timer controlled by the chosen key. Subsequent choices of that key reset and started the timer again. This timer stopped only when (a) reinforcement occurred (2.5-s access to grain), (b) the other side key was pecked, or (c) 2 s had elapsed since the last choice of the key. As a consequence, each timer associated with each key operated so long as the bird was pecking a given key with interresponse times less than 2 s.

Whenever either 2-s timer operated, so did another timer (preference timer). When the preference timer equaled a predetermined duration, the proportion of this duration due to the operation of the right key's 2-s timer was calculated. For the first four conditions of the experiment, this duration was 6 s; and for the last four conditions, the preference timer's duration was 4 min.

The proportion of time allocated to the right key during either the 6-s or 4-min preference-timer period was used to define the reinforcements/hour delivered by a constant-probability VI schedule for responding on each of the two keys during the subsequent 6-s or 4-min period. The specific functions relating reinforcements/hour to relative right-key time allocation for all eight conditions of the experiment are presented in Figure 1.

To illustrate this figure's interpretation, consider the top panel that presents, for Conditions 1 and 6, the reinforcements/hour allocated to each key as a function of the relative time on the right key. When relative time on the right had been between 0 and 0.25, pecks on the right key produced VI reinforcement at the rate of 240/hour and on the left key at 30/hour; when relative right-key allocations were between 0.75 and 1, these reinforcement rates were reversed; and when right-key allocations were between 0.25 and 0.75, VI reinforcement rates for both keys equaled 30/hour.

When the VI schedule assigned a reinforcer, the next peck on that key could pro-

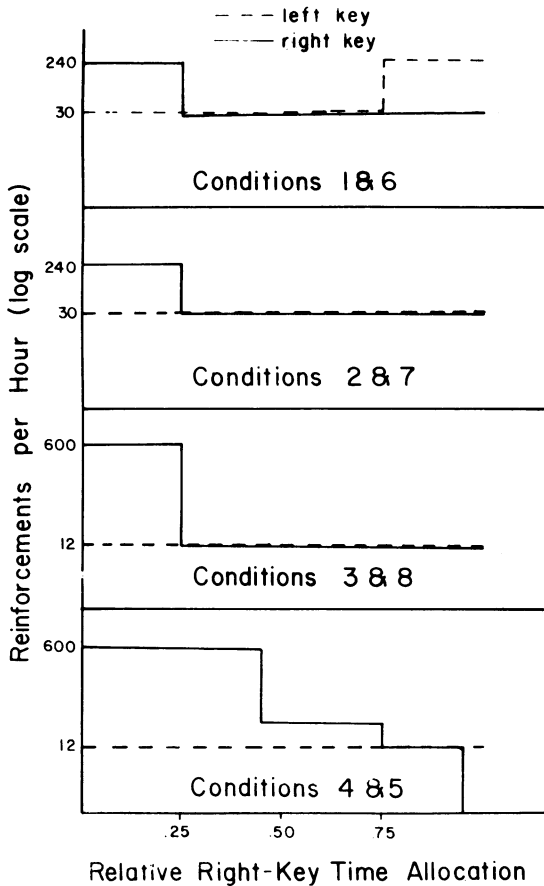


Fig. 1. Scheduled local reinforcement rates for each key as a function of relative time allocated to the right key. Conditions to which schedules apply are identified in each panel.

duce it, unless the prior response had been reinforced or had been on the other key. In this case, the response-initiated timer had to operate for at least 1 s before another response could produce the reinforcer.

Daily sessions terminated after 60 reinforcers if this reinforcement total was obtained within 90 min of session time. If not, the session ended when the preference timer (set at 6 s or 4 min, depending on the condition) next timed out after 90 min of session time. During each session, the keylights and houselight were illuminated except during the hopper cycle.

Each experimental condition lasted between two and three weeks. Conditions were altered at experimenter convenience rather than on the basis on any stability criterion.

Table 1
Order of Experimental Conditions

Condition	Preference Timer (sec)	Sessions
1-S	6	20
2-S	6	14
3-S	6	16
4-S	6	14
5-M	240	15
6-M	240	20
7-M	240	17
8-M	240	15

All data analyses presented are based on the last five sessions of each condition, except for Condition 6 in which data were summed across the last ten sessions.

Table 1 lists the sequence of experimental conditions, the duration of the preference timer in seconds, and the number of sessions for each condition.

RESULTS

Figure 2 presents the log ratio of behavior measured in terms of pecks (left column of panels) and time allocation (right column of panels) as a function of the log ratio of reinforcement. The dashed line through each panel defines the perfect-matching locus. The data produced with the preference timer set at 4 min lie closer to this function than do the data produced with the preference timer set at 6 s. However, both data sets reveal undermatching; increases in reinforcement ratios produced less-than-unitary changes in behavior ratios. To quantify this tendency, we pooled all data from the 6-s timer condition and by the method of least squares determined the line of best fit for responses and time. These equations were $Y = 0.381X + 0.111$ and $Y = 0.271X + 0.127$, respectively, and their respective correlation coefficients were 0.91 and 0.80. The same functions for the 4-min timer condition were, respectively, $Y = 0.676X + 0.04$ and $Y = 0.677X + 0.113$, with correlation coefficients of 0.83 and 0.94.

Figure 3 presents R_D (see Equation 3) as a function of the log of the ratio of reinforcements for the 6-s and 4-min preference-

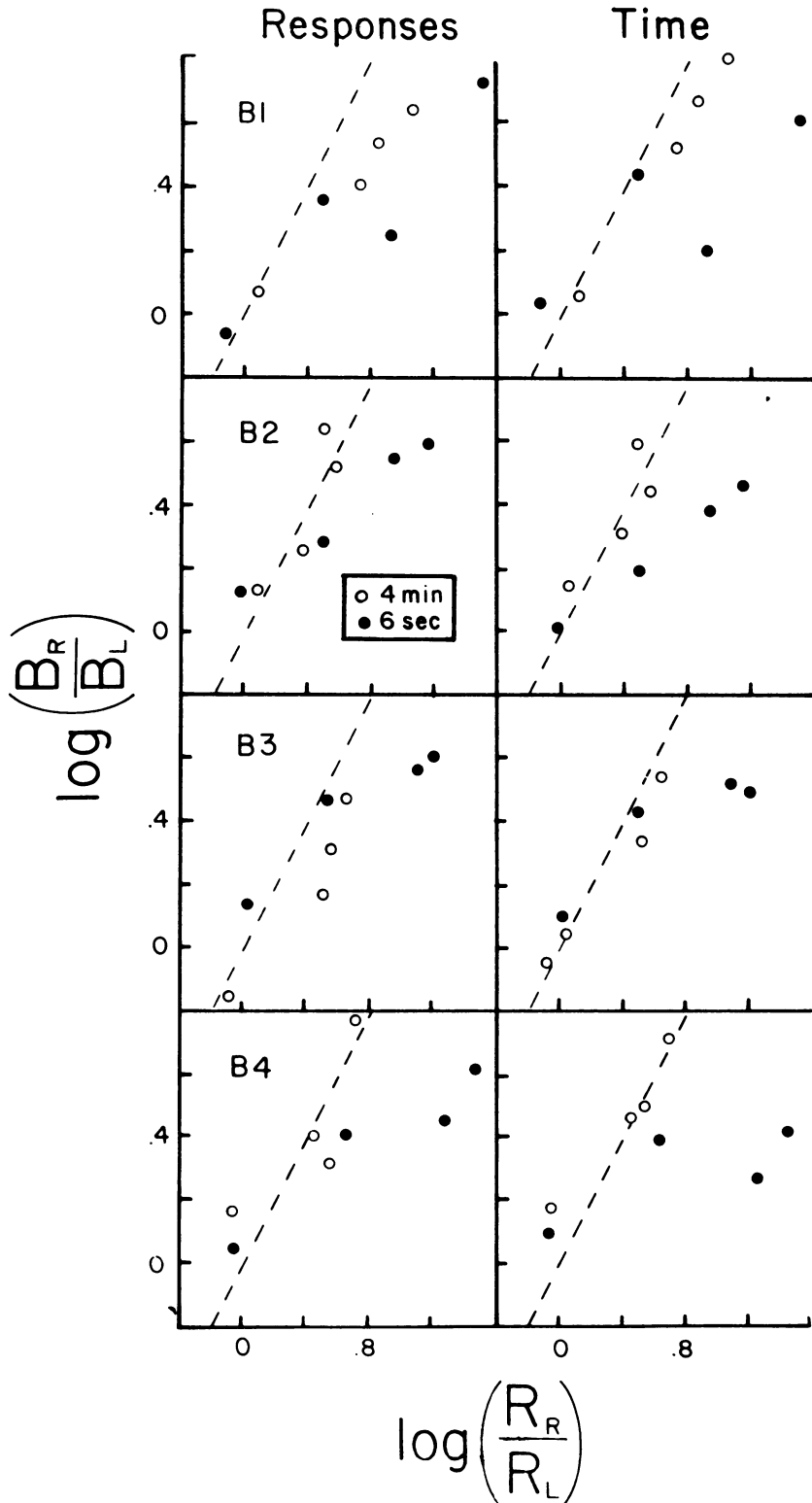


Fig. 2. Log ratio of behavior to log ratio of reinforcement for each of 4 birds.

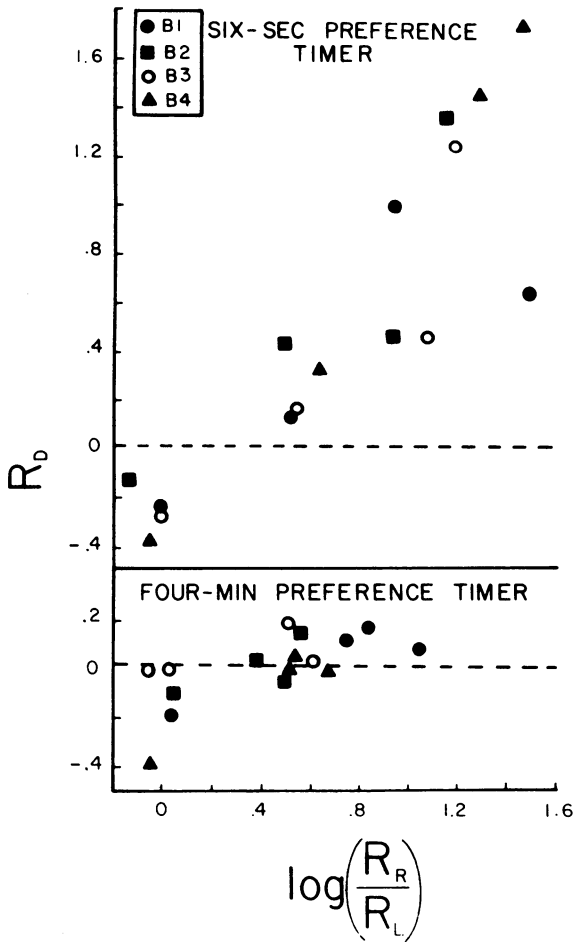
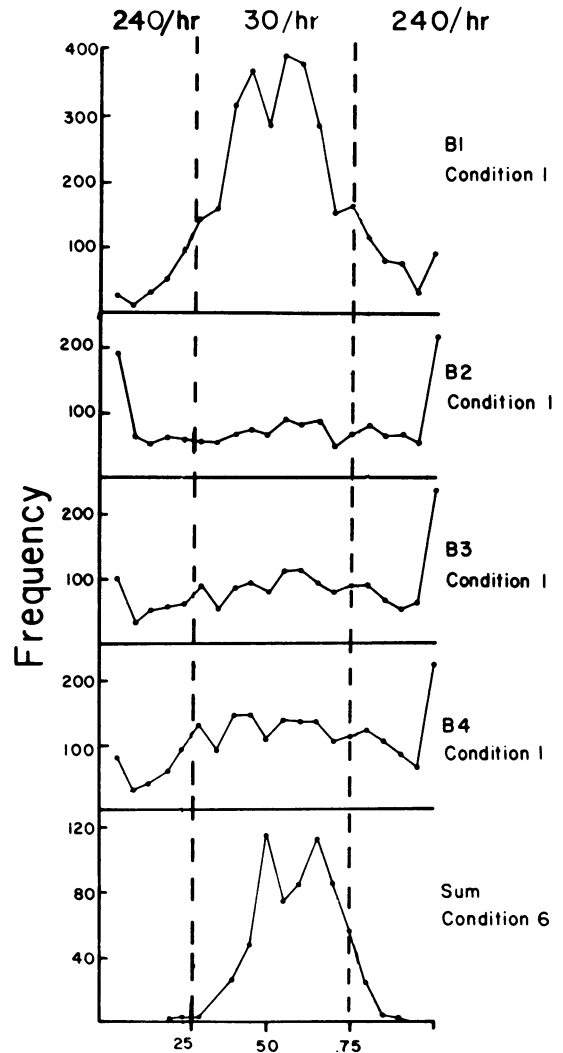


Fig. 3. Difference in local reinforcement rates (R_D) for each bird as a function of the log of the reinforcement ratio. Dashed lines define perfect melioration ($R_D = 0$).

timer data. The dashed line in each panel presents the prediction of melioration ($R_D = 0$). The “4 min” data lie much closer to this line than do the “6 s” data. Nevertheless, even in the case of the former data set, there may be a small tendency for R_D to increase with increasing reinforcement ratios ($p = .06$ with Jonckheere’s [1954] test for significant trends); and in the case of the “6 s” data, this tendency is marked.

For Conditions 1 and 6, reinforcement rates were highest (240/hour) when schedule adjustments were based on relative right-key time allocations that were either greater than 0.75 or less than 0.26 and were lowest (30/hour) when these allocations were be-



Relative Right-Key Time Allocation

Fig. 4. Frequency distribution of relative right-key time allocations. Individual subject data (top 4 panels) are presented for a 6-s preference-timer condition (Condition 1). Bottom panel presents function for 4-min timer condition (Condition 6) summed across all subjects.

tween 0.26 and 0.75. The top four panels of Figure 4 present for individual subjects the frequency of schedule adjustments based on relative time allocations that fell within either the 240/hour or the 30/hour reinforcement categories for the 6-s timer condition. The bottom panel presents the same data for the 4-min preference condition summed across all subjects for the last ten sessions.

This figure shows that when the 6-s timer was in effect, for all birds except B1 the modal relative time allocations fell within the high-reinforcement category. However, when the 4-min timer was in effect, very few of their relative allocations adjustments were in the high-reinforcement category.

The procedurally induced lag between measurement of time allocation and assignment of reinforcement rates permits a subject to maximize reinforcement rates by switching between keys with an ICT equal to the preference-timer period. One could detect this sort of pattern by plotting relative time allocation in one period as a function of relative time allocation in the next period. Toward this end, a matrix of counters recorded during Conditions 1 and 6 each subject's relative right-key time allocations each time the preference timer reached 6 s (Condition 1) or 4 min (Condition 6) as a function of what its relative time allocation had been during the immediately prior preference-timer period. These data, presented in Figure 5, are based on medians of distributions of relative time allocations. The curves for individual subjects for Condition 1 show an inverse relation between subsequent and prior preference-timer periods: Whichever key was preferred in the prior preference-timer interval was less preferred in the following interval.

Also presented in Figure 5 is a curve based on the summed data from Condition 6. Data points based on fewer than 30 observations are excluded because we question the stability of means based on small sample sizes. This function from the 4-min condition differs from the others: There is no obvious relation between relative time allocation in the prior versus subsequent preference-timer period.

DISCUSSION

When the 6-s preference timer was in effect (Conditions 1 through 4), the results of the present study were incompatible with either matching theory or melioration. Regarding matching theory, behavior-ratio

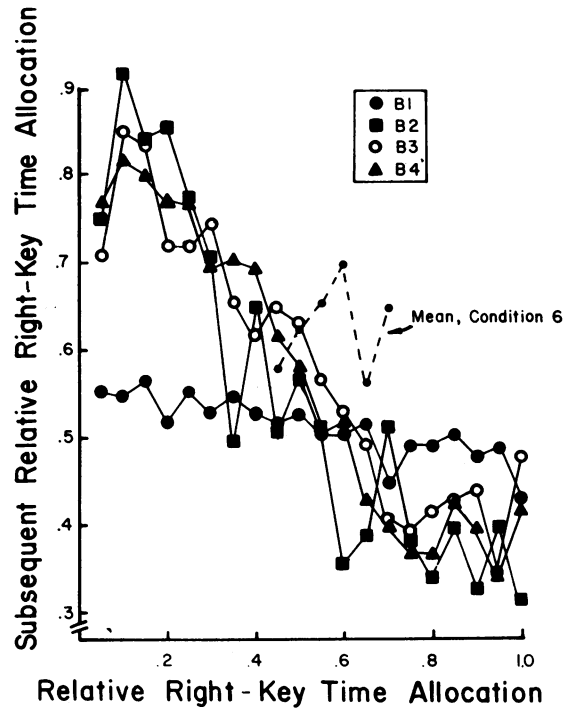


Fig. 5. Relative right-key time allocation during a preference-timer period as a function of the relative right-key allocation during the prior preference-timer period for each subject in Condition 1 and averaged across all subjects for Condition 6.

functions showed severe undermatching (see Figure 2). In fact, the slopes of the lines of best fit for responses and time, both being below 0.4, are unrepresentative of typical matching data. For example, in his review of 103 choice data sets, Baum (1979) found that the slope for linear best-fit functions ranged from 0.4 to 2.0 with a mean of 1.0. Regarding melioration, the 6-s preference-timer data in Figure 3 show that animals failed to minimize differences between local reinforcement rates ($R_D = 0$). Instead, these differences increased as relative right-key reinforcement rates increased.

The data from Figures 4 and 5 amplify the molar analysis presented above by offering a molecular portrayal of time allocation in this study. The 6-s data from these figures also seem incompatible with matching or melioration. Except for B1 in Figure 4, we see from the U-shaped distribution of local time allocations that birds with the 6-s preference timers tended to have modes at extreme left-

and right-key time allocations. This outcome is important because even if matching and melioration had been descriptively adequate at a molar level in Figures 2 and 3, they would still have rendered a false portrayal of the molecular processes of choice: By aggregating behavior over large blocks of time, the matching and melioration equations deny the relevance of a local process in choice; yet, the operation of such a process is clearly evidenced in the bimodal distributions of Figure 4.

Although these bimodal functions are not predicted by matching and melioration theories, they are predicted by molecular maximizing because the highest reinforcement rates (240/hour) were available only at the extreme local time allocations, where the modes were found. The nature of the local process producing these bimodal distributions is seen in the 6-s preference-timer data from Figure 5. There we see strong evidence of behavioral patterning. This sequencing of time allocations is exactly what would be expected by maximizing of local reinforcement likelihoods, because maximizing reinforcement with this study's choice contingencies requires strict alternation of time allocations from one schedule to the other over successive 6-s periods. Figure 5 makes clear that animals reasonably approximated this strategy. Indeed, taken together, we believe the data from Figures 4 and 5 argue convincingly that choice with a 6-s preference timer was controlled at the level of local time allocation by a maximizing process.

Although these 6-s timer data appear better explained by molecular maximizing than by matching or melioration, these latter, molar accounts appear useful when applied to the choice data where the 4-min preference timer was used (Conditions 5 through 8). In Figure 2, the linear best-fit function of a matching analysis had a slope of 0.68—a degree of undermatching well within the range reported by Baum for studies in which the matching law has been successfully applied. Similarly, Figure 3 shows that the melioration account does better when reinforcement rates are based on time allocations

summed over 4 min of responding. Although R_D seems to increase with increases in the right-key reinforcement ratio, this trend is much more modest than for the 6-s timer data, and for many data points the melioration prediction of $R_D = 0$ seems quite acceptable.

The molecular analyses offered by Figures 3 and 4 of the 4-min timer data are also compatible with matching and melioration. In the bottom panel of Figure 3, virtually all schedule adjustments were within the reduced reinforcement range (30/hour). This outcome can be explained in terms of matching and melioration, but it is incompatible with maximizing the overall rate of reinforcement. Moreover, the clear unimodality of the distribution argues that the averaging of time allocations, as interpreted by melioration and matching theory, may be the proper characterization of the psychological process by which choice occurred. Finally, the Condition-6 data in Figure 5 show no systematic trend in sequencing time allocations—a result consistent with molar accounts of choice.

The data from the present study suggest a complementarity between molecular maximizing and melioration. When the procedure permits the relation between choice and reinforcement to be integrated over brief time spans (i.e., 6 s), we see strong evidence of a maximizing-based patterning of time allocations (see Silberberg & Ziriaux, 1982); yet, when this integration must be over long time spans (i.e., 4 min), the choice data seem more compatible with molar accounts such as melioration and matching. One could interpret these data as showing that choice can be controlled at either the molar or molecular level, depending on the choice procedure used; however, this is not an interpretation we favor because we believe the results of this study can be explained solely in terms of molecular maximizing. In particular, we argue below that molecular maximizing controlled choice in both the 6-s and 4-min conditions, but its manifestations were weakened in the latter conditions by the procedural constraint that the choice-

Table 2
Summed data from last five sessions of each condition, except for 6-M, which is based on ten sessions.

Condition	Responses		Time (Minutes)			Reinforcers		Changeovers	Schedule
	Left	Right	Left	Right	Total	Left	Right		Adjustments
1 - S									
B1	19941	17961	183.5	199.9	429.4	150	113	5700	3286
B2	13960	18936	92.0	98.0	249.7	152	148	1479	1629
B3	5202	7339	87.4	111.6	259.3	146	154	1735	1705
B4	16482	18503	114.0	142.0	291.5	158	142	2373	2194
2 - S									
B1	10707	24601	99.6	281.4	440.1	56	190	3254	3266
B2	21062	41165	145.7	228.7	439.4	64	199	3061	3209
B3	5758	17210	95.3	264.8	441.0	51	181	1993	3087
B4	11671	30008	104.0	263.2	440.4	46	203	2507	3147
3 - S									
B1	11183	20036	126.3	198.5	430.0	28	241	3801	3248
B2	12935	45946	107.9	266.8	442.6	19	164	3084	3747
B3	3997	14794	77.5	264.0	442.7	14	168	2425	3415
B4	7321	20739	91.6	176.4	331.8	15	285	1993	2680
4 - S									
B1	4736	25548	61.7	253.9	437.1	6	184	3122	3156
B2	8250	32494	57.6	164.8	284.3	20	281	1919	2224
B3	2606	10731	57.8	183.3	325.6	18	283	1710	2411
B4	4927	20402	57.0	152.7	289.2	10	292	1768	2097
5 - M									
B1	8421	21597	72.5	246.3	366.3	12	68	2884	80
B2	7790	34988	53.3	213.7	370.5	15	48	1620	67
B3	4281	13305	61.6	221.4	368.3	13	54	1190	71
B4	3710	23508	41.6	221.4	368.2	8	38	691	66
6 - M (ten sessions)									
B1	35344	42900	289.9	467.2	911.5	202	233	5840	190
B2	48507	67767	306.8	442.3	902.8	171	198	7586	188
B3	32980	22273	399.8	373.3	911.3	199	179	2543	194
B4	29701	43642	293.1	456.1	888.9	282	258	2135	188
7 - M									
B1	7164	25117	67.3	311.3	458.0	22	152	970	95
B2	12864	43504	101.6	281.0	457.8	33	125	3211	96
B3	8323	12663	104.2	234.5	450.2	38	129	1347	85
B4	10791	22677	93.9	302.2	460.7	37	130	921	99
8 - M									
B1	5686	26153	50.4	324.2	463.6	5	59	1478	94
B2	20728	39088	121.8	256.8	451.5	23	56	3387	95
B3	14320	11701	169.9	196.7	459.7	38	42	1161	92
B4	7704	19899	75.9	231.1	461.1	14	40	496	77

reinforcement feedback function be integrated over a 4-min span for maximizing to occur.

As evidence of the weakened manifesta-

tions of molecular maximizing, note in Figure 2 that pigeons in the 4-min conditions tended to undermatch substantially. In this study, undermatching was produced by

pigeons' choosing the left key "too" frequently. However, a beneficial consequence of too-frequent selection of the left key must be acknowledged: It increased the likelihood that right-key choices, when they occurred, would access the high reinforcement rates produced by left-key preferences (see Figure 1). To the extent that animals undermatched more than is typical on concurrent VI schedules (slope of 0.68 in Figure 2 vs. average matching function of about 0.8; see Myers & Myers, 1977), we may be witness to the operation of maximizing principles even with a 4-min preference timer.

A similar conclusion can be drawn from the melioration analysis in Figure 3. Certainly the melioration prediction of $R_D = 0$ does a better job for the 4-min conditions than for the 6-s conditions. Nevertheless, the same tendency toward maximizing can be seen in both data sets because as right-key reinforcement ratios increase, so does R_D , even for the 4-min conditions. This outcome is due to animals' spending more time on the left key than is dictated by the matching equation. As Figure 1 makes clear, the advantage of this tendency is that it increases the prospects of tapping the zone of higher reinforcement rates for behavior ratios favoring the left key. Thus, the tendency for R_D to increase with right-key reinforcement is consistent with the notion that animals are trying to maximize reinforcement rates in the 4-min condition.

These arguments would be strengthened were it demonstrated that molecular-maximizing behavior actually generates molar and molecular data such as those from the present study. To test this thesis, we present below a computer simulation of the Vaughan study where the algorithm governing choice produces such an outcome.

SIMULATION

In this simulation, two *stat* birds responded 1/s to the choice procedure described in the Method section. For one bird the reinforcement contingencies were those of Condition 1 (6-s preference timer), and for the other the contingencies duplicated those of Con-

dition 6 (4-min preference timer). For the first 20 reinforcers on each schedule, each *stat* bird switched between schedules every 10 responses, generating an ICT of 10-s. Whenever a response produced a reinforcer, the time between the prior changeover and the response producing reinforcement (CO-to-rf delay) was stored in *reinforcement memory* in the order in which it occurred. When 20 CO-to-rf delays were in *reinforcement memory* for each schedule, control of choice was given to *reinforcement memory*. From this memory the CO-to-rf delay that occurred 20 reinforcers earlier to one schedule in the *stat* bird's history defined the duration of the next ICT to the *alternate* schedule. For example, if the CO-to-rf delay 20 reinforcers earlier for Schedule A equaled 8 s, an 8-s ICT would then be emitted to Schedule B. If after, say, 6 s a reinforcement occurred, that value replaced the historically oldest CO-to-rf value in *reinforcement memory* for Schedule B. Nevertheless, the ICT would continue for 2 s more to complete the 8-s ICT specified by Schedule A's *reinforcement memory*. Once this ICT was emitted to Schedule B, the *stat* bird switched back to Schedule A and emitted an ICT equal to the historically oldest CO-to-rf delay in *reinforcement memory* from Schedule B. If reinforcement occurred during this ICT, the CO-to-rf delay produced entered the *reinforcement memory*, for Schedule A, replacing the oldest CO-to-rf delay in that list. Consequently, each *stat* bird reproduced, as ICTs, their 20 most recent CO-to-rf delays to the alternate schedule throughout each session in the order in which they occurred. They thus switched schedules whenever memory indicated that the time they had spent on the current schedule exceeded that which had previously been sufficient to produce reinforcement on the alternate schedule.

After 400 reinforcers were obtained by each *stat* bird, response and time allocations were recorded for data analysis. Data collection continued until each *stat* bird's preference timer had made 500 schedule adjustments (50 min and 2000 min for Conditions 1 and 6, respectively).

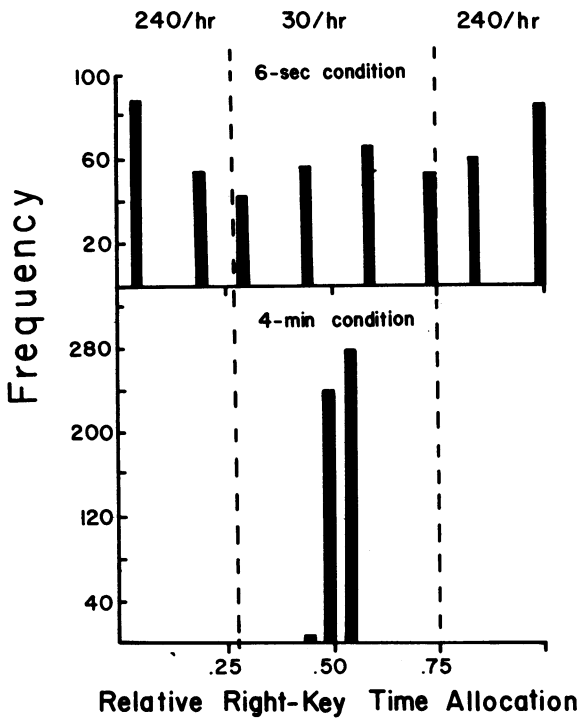


Fig. 6. Frequency distribution of relative right-key time allocations during 6-s (top panel) and 4-min (bottom panel) preference-timer periods for two *stat* birds.

Results

In terms of molar measures, the *stat* bird exposed to Condition 1 (6-s preference timer) had relative right-key behavior and reinforcement rates of 0.51 and 0.53, respectively. For the other *stat* bird (Condition 6, 4-min preference timer), these values were 0.5 and 0.51, respectively.

Figure 6 presents the frequency distribution of relative time allocations for the *stat* birds exposed to the 6-s condition and the 4-min condition. The data from the 6-s condition are bimodal with each mode being in the high-reinforcement zone (240/hour). The function for the 4-min condition, on the other hand, is unimodal with all data points being in the low-reinforcement zone (30/hour).

Figure 7 presents the mean relative right-key time allocation during a given preference-timer period as a function of the relative right-key time allocation during the prior preference period for the 6-s and 4-min conditions. For the former condition, this

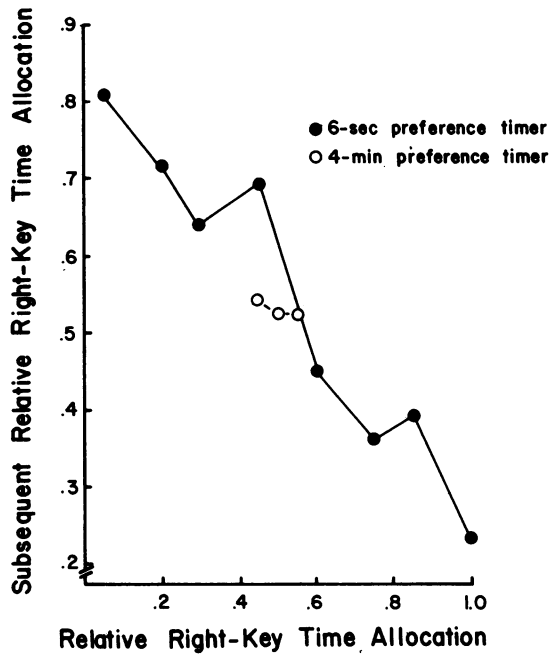


Fig. 7. Relative right-key time allocation during a preference-timer period as a function of the relative right-key allocation during the prior preference-timer period for one *stat* bird in the 6-s condition (filled circles) and another in the 4-min condition (unfilled circles).

function clearly has a negative slope, a result indicating that the *stat* bird in the 6-s condition tended to switch between schedules when the 6-s clock associated with a schedule timed out. For the 4-min clock, no such patterning is apparent. In this condition, the relative time allocation was essentially static regardless of the relative time allocation during the prior preference period.

Discussion

In this simulation, molecular-maximizing behavior was simulated by taking the CO-to-rf delays generated by one schedule and reproducing them as ICTs on the other. To illustrate how this simple rule can produce molecular maximizing, consider its application when concurrent VI 1-min VI 2-min schedules are used on Vaughan's procedure. The distribution of CO-to-rf delays for the VI 1-min schedule should be, on average, half those for the VI 2-min schedule. By using each schedule's CO-to-rf delay distribution to define ICTs to the alternate

schedule, the ICTs emitted should produce time-based matching. Because matching on these schedules is compatible with maximizing (see Rachlin et al., 1976), this algorithm can be fairly described as maximizing; and because individual, brief CO-to-rf delays were used to define time allocation, this algorithm can also be labeled as molecular.

Meeting these criteria makes these data compatible with molecular maximizing. We can now address their purpose: Do the data generated look similar to the data from the 6-s and 4-min conditions (Conditions 1 and 6) from our experiment? To a first approximation, the answer is yes. Regarding molar choice, we see in the behavior and reinforcement ratios of the simulation that, as in the experiment itself, they closely approximate the predictions of melioration and matching; and regarding the simulated molecular functions in Figures 6 and 7, they are similar in form to the functions in Figures 4 and 5 generated by real birds in Conditions 1 and 6. In sum, these data show that a simple molecular-maximizing algorithm can generate choice data similar to those found in the prior experiment.

GENERAL DISCUSSION

Vaughan (1981) used his procedure to compare the predictive adequacy of three accounts of choice: matching, melioration, and molar maximizing. In making this test, relative time allocations were calculated every 4 min and those calculations determined reinforcement rates for the next 4 min. The present study reproduced this procedure in several of its conditions, and in the others replaced the 4-min timer with a 6-s timer. With this 6-s timer it was possible to test for control of choice by a fourth principle, molecular maximizing; and the results of this test could be directly compared with those from the 4-min timer conditions used by Vaughan.

In terms of molar and molecular measures, the results from the 6-s conditions could be explained only in terms of molecular-maximizing principles; however, the

results from the 4-min conditions were more problematic: Although the contribution of molecular maximizing to the choice data obtained could be discerned in the molar data (Figures 2 and 3), the molecular data (Figures 4 and 5) seemed, at first blush, incompatible with molecular maximizing. To evaluate this apparent incompatibility, simulations were run in which *stat* birds, following a molecular-maximizing algorithm, responded on the Vaughan procedure with timers set at 6 s and 4 min. The results of these simulations showed this incompatibility to be more apparent than real; simulated and actual experimental findings were similar for the 6-s and 4-min conditions. These results establish that of the models considered, molecular maximizing best describes choice allocation on the Vaughan procedure.

On first consideration, this outcome seems to contradict several studies that have recently reported antimaximizing data (Herrnstein & Heyman, 1979; Heyman, 1979; Heyman & Luce, 1979; Mazur, 1981; Nevin, 1979; Vaughan, 1981). However, only two of these studies—Heyman's and Nevin's—actually claimed to test molecular maximizing (the others were designed to test molar maximizing); and in both these cases, molecular-maximizing theorists have found their arguments unconvincing (e.g., see Hinson & Staddon, 1983; Houston & McNamara, 1981; Silberberg et al., 1978; Silberberg & Ziriax, 1982, pp. 135-138).

In fact, we know of no data that contradict the view that choice is controlled molecularly. Moreover, this conclusion is consistent with recent single-schedule work showing that response rate on a schedule is controlled not by a molar variable (e.g., the feedback function between response rate and reinforcement rate; see Rachlin, 1978), but by a molecular variable (e.g., reinforced interresponse-time distribution; see Peele, Casey, & Silberberg, 1984). Thus, we may be closing in on a unified theory of performance effects based on the proposition that behavior is organized at a molecular level by the local relation between behavior and reinforcement.

REFERENCES

- Baum, W. M. (1979). Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, *32*, 269-281.
- de Villiers, P. (1977). Choice in concurrent schedules and a quantitative formulation of the law of effect. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior* (pp. 233-287). Englewood Cliffs, NJ: Prentice-Hall.
- Herrnstein, R. J., & Heyman, G. M. (1979). Is matching compatible with reinforcement maximization on concurrent variable interval, variable ratio? *Journal of the Experimental Analysis of Behavior*, *31*, 209-223.
- Herrnstein, R. J., & Vaughan, W., Jr. (1980). Melioration and behavioral allocation. In J. E. R. Staddon (Ed.), *Limits to action: The allocation of individual behavior* (pp. 143-176). New York: Academic Press.
- Heyman, G. M. (1979). A Markov model description of changeover probabilities on concurrent variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, *31*, 41-51.
- Heyman, G. M., & Luce, R. D. (1979). Operant matching is not a logical consequence of maximizing reinforcement rate. *Animal Learning & Behavior*, *7*, 133-140.
- Hinson, J. M., & Staddon, J. E. R. (1983). Hill-climbing by pigeons. *Journal of the Experimental Analysis of Behavior*, *39*, 25-47.
- Houston, A. I., & McNamara, J. (1981). How to maximize reward rate on two variable-interval paradigms. *Journal of the Experimental Analysis of Behavior*, *35*, 367-396.
- Jonckheere, A. R. (1954). A test of significance for the relation between m rankings and k ranked categories. *British Journal of Statistical Psychology*, *7*, 93-100.
- Mazur, J. E. (1981). Optimization theory fails to predict performance of pigeons in a two-response situation. *Science*, *214*, 823-825.
- Myers, D. L., & Myers, L. E. (1977). Undermatching: A reappraisal of performance on concurrent variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, *27*, 203-214.
- Nevin, J. A. (1979). Overall matching versus momentary maximizing: Nevin (1969) revisited. *Journal of Experimental Psychology: Animal Behavior Processes*, *5*, 300-306.
- Peele, D. B., Casey, J., & Silberberg, A. (1984). Primacy of interresponse-time reinforcement in accounting for rate differences under variable-ratio and variable-interval schedules. *Journal of Experimental Psychology: Animal Behavior Processes*, *10*, 149-167.
- Rachlin, H. (1978). A molar theory of reinforcement schedules. *Journal of the Experimental Analysis of Behavior*, *30*, 345-360.
- Rachlin, H., Green, L., Kagel, J. H., & Battalio, R. C. (1976). Economic demand theory and psychological studies of choice. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 10, pp. 129-154). New York: Academic Press.
- Shimp, C. P. (1966). Probabilistically reinforced choice behavior in pigeons. *Journal of the Experimental Analysis of Behavior*, *9*, 443-455.
- Shimp, C. P. (1981). The local organization of behavior: Discrimination of and memory for simple behavioral patterns. *Journal of the Experimental Analysis of Behavior*, *36*, 303-315.
- Silberberg, A., Hamilton, B., Ziriaux, J. M., & Casey, J. (1978). The structure of choice. *Journal of Experimental Psychology: Animal Behavior Processes*, *4*, 368-398.
- Silberberg, A., & Ziriaux, J. M. (1982). The inter-changeover time as a molecular dependent variable in concurrent schedules. In M. L. Commons, R. J. Herrnstein, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 2. Matching and maximizing accounts* (pp. 131-151). Cambridge, MA: Ballinger.
- Vaughan, W., Jr. (1981). Melioration, matching, and maximization. *Journal of the Experimental Analysis of Behavior*, *36*, 141-149.

Received November 16, 1983

Final acceptance November 21, 1984